OPERATING INSTRUCTIONS

TYPE 874-LBA

SLOTTED LINE

874-LBA

GENERAL RADIO COMPANY

Dept. 201

G

OPERATING INSTRUCTIONS

TYPE 874-LBA

SLOTTED LINE

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GENERAL RADIO COMPANY
WEST CONCORD, MASSACHUSETTS, USA

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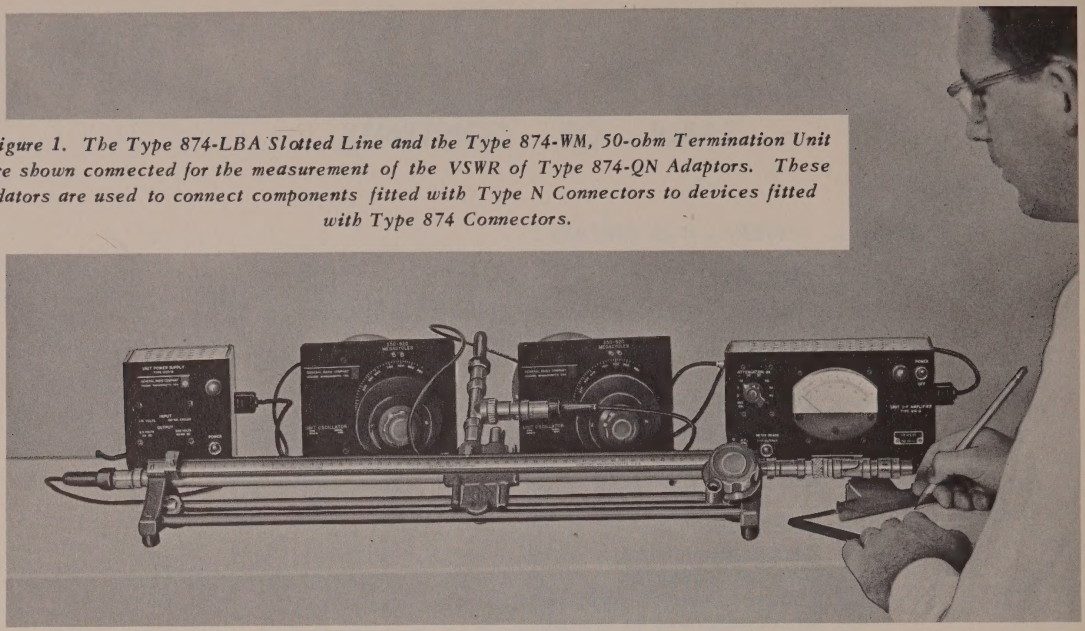


Figure 1. The Type 874-LBA Slotted Line and the Type 874-WM, 50-ohm Termination Unit are shown connected for the measurement of the VSWR of Type 874-QN Adaptors. These adators are used to connect components fitted with Type N Connectors to devices fitted with Type 874 Connectors.

SPECIFICATIONS

Characteristic Impedance: 50 ohms, ±0.5%.

Probe Travel: 50 cm. Scale calibrated in mm.

Scale Accuracy: ±(0.1 mm +0.05%).

Frequency Range: 300 to 5000 Mc. At 300 Mc the slotted line covers one half wavelength. Operation below 300 Mc is possible with slightly reduced accuracy.

Constancy of Probe Penetration: ±1½%.

Residual VSWR:

1.025 at 1000 Mc	1.07 at 4000 Mc
1.04 at 2000 Mc	1.1 at 5000 Mc
1.055 at 3000 Mc	

Accessories Supplied: Storage box and spare drive cable.

Accessories Required: Adjustable Stub (Type 874-D20) for tuning the crystal rectifier when audio-frequency detector or microammeter is used; suitable detector and generator; one each, Types 874-R22 and 874-R34 Patch Cords, for generator and detector connections.

Other Accessories Available: See List of Type 874 Components at the rear of this manual.

Dimensions: 26 by 4½ by 3½ inches (660 by 115 by 90 mm), over-all.

Net Weight: 8½ pounds (3.9 kg).

Several copies of Smith Charts are supplied with the Slotted Line. Additional copies can be obtained from General Radio at the following prices:

Quantity	Price	Quantity	Price
50	$2.00	500	$14.00
100	3.75	1000	25.00
200	7.00		

When ordering, please specify Impedance Coordinates (Form 756-Z), Admittance Coordinates (Form 756-Y), Normalized Coordinates (Form 756-N), or Normalized Coordinates with Expanded Center (Form 756-NE).

U.S. Patent No. 2,548,457

SECTION **1**

GENERAL DESCRIPTION

One of the important basic measuring instruments used at ultra-high frequencies is the slotted line. With it, the standing-wave pattern of the electric field in a coaxial transmission line of known characteristic impedance can be accurately determined. From a knowledge of the standing-wave pattern several characteristics of the circuit connected to the load end of the slotted line can be obtained. For instance, the degree of mismatch between the load and the transmission line can be calculated from the ratio of the amplitude of the maximum of the wave to the amplitude of the minimum of the wave. This is called the voltage standing-wave ratio, VSWR. The load impedance can be calculated from the standing-wave ratio and the position of a minimum point on the line with respect to the load. The wavelength of the exciting wave can be measured by obtaining the distance between minima, preferably with a lossless load to obtain the greatest resolution, as successive minima or maxima are spaced by half wavelengths. The properties outlined above make the slotted line valuable for many different types of measurements on antennas, components, coaxial elements, and networks.

The Type 874-LBA Slotted Line is designed to measure the standing-wave pattern on a 50-ohm coaxial transmission line, over a frequency range from about 300 to 5000 Mc. A small probe mounted on a sliding carriage extends through a slot into the region between the inner and outer conductors of a coaxial line and samples the electric field in the line. The probe is connected to a detector, and the variation in electric field intensity, and hence the voltage along the line, can be determined from the variation in detector output, as the carriage is moved along the line.

SECTION **2**

THEORY

2.1 CHARACTERISTIC IMPEDANCE AND VELOCITY OF PROPAGATION.

A transmission line has uniformly distributed inductance and capacitance, as shown in Figure 1. The series resistance due to conductor losses and the shunt resistance due to dielectric losses are also uniformly distributed, but they will be neglected for the present. The square root of the ratio of the inductance per unit length, L, to the capacitance per

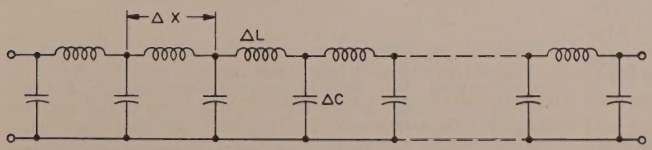


Figure 1. Circuit showing the distribution of inductance and capacitance along a transmission line.

unit length, C, is defined as the characteristic impedance, Z_o, of the line.

$$Z_o = \sqrt{\frac{L}{C}} \qquad (1)$$

This is an approximation which is valid when line losses are low. It gives satisfactory results for most practical applications at high frequencies.

In the next paragraph, transmission-line behavior will be discussed in terms of electromagnetic waves traveling along the line. The waves travel with a velocity, v, which depends on L and C in the following manner:

$$v = \frac{1}{\sqrt{LC}} \qquad (2)$$

If the dielectric used in the line is air, (permeability unity), the product of L and C for any uniform line is always the same. The velocity is equal to the velocity of light, c, (3×10^{10} cm/sec). If the effective dielectric constant, K, is greater than unity, the velocity of propagation will be the velocity of light divided by the square root of the effective dielectric constant.

$$v = \frac{c}{\sqrt{K}} \qquad (3)$$

The relationship between frequency, f, and wavelength, λ, in the transmission line is

$$\lambda f = v \qquad (4a)$$

$$f = \frac{v}{\lambda} \qquad (4b)$$

$$\lambda = \frac{v}{f} \qquad (4c)$$

If the dielectric is air (permeability is unity),

$$\lambda f = 3 \times 10^{10} \text{ cm/sec} \qquad (4d)$$

if λ is in centimeters and f is in cycles per second.

2.2 TRAVELING AND STANDING WAVES.

The performance of a transmission line having a uniform characteristic impedance can be explained in terms of the behavior of the electromagnetic wave that travels along the line from the generator to the load, where all or a portion of it may be reflected with or without a change in phase, as shown in Figure 2a. The reflected wave travels in the opposite direction along the line, back toward the generator. The phases of these waves are retarded linearly 360° for each wavelength traveled.

The wave traveling from the generator is called the incident wave, and the wave traveling toward the

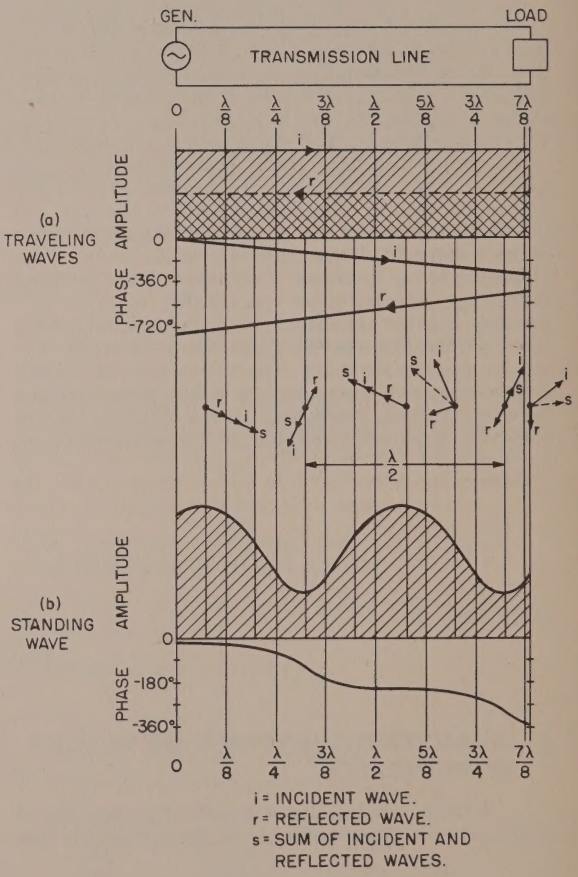


Figure 2. (a) Chart showing the variations in the amplitude and phase of incident and reflected waves along a transmission line. (b) The vector combination of the incident and reflected waves at various points along the line is illustrated and the resultant standing wave produced by the combination of the two waves is plotted.

generator is called the reflected wave. The combination of these two traveling waves produces a stationary interference pattern which is called a standing wave, as shown in Figure 2b. The maximum amplitude of the standing wave occurs when the incident and reflected waves are in phase or when they are an integral multiple of 360° out of phase. The minimum amplitude occurs when the two waves are 180°, or an odd integral multiple thereof, out of phase. The amplitude of the standing wave at other points along the line is the vector sum of incident and reflected waves. Successive minima and maxima are spaced, respectively, a half-wavelength along the line, as shown in the figure.

The magnitude and phase of the reflected wave at the load, relative to the incident wave, are functions of the load impedance. For instance, if the load impedance is the same as the characteristic impedance of the transmission line, the incident wave is totally absorbed in the load and there is no reflected wave. On the other hand, if the load is lossless, the incident wave is always completely reflected, with no change in amplitude but with a change in phase.

A traveling electromagnetic wave actually consists of two component waves: a voltage wave and a current wave. The ratio of the magnitude and phase of the incident voltage wave, E_i, to the magnitude and phase of the incident current wave, I_i, is always equal to the characteristic impedance, Z_o. The reflected waves travel in the opposite direction from the incident waves, and consequently the ratio of the reflected voltage wave, E_r, to the reflected current wave, Ir, is $-Z_o$. Since the characteristic impedance in most cases is practically a pure resistance,[1] the incident voltage and current waves are in phase with each other, and the reflected voltage and current waves are 180° out of phase.

$$\frac{E_i}{I_i} = Z_o \qquad (5a)$$

$$\frac{E_r}{I_r} = -Z_o \qquad (5b)$$

Equations (5a) and (5b) are valid at all points along the line.

The magnitude and phase of the reflected voltage wave, E_r, relative to the incident wave, E_i, at the load is called the reflection coefficient, Γ, which can be calculated from the expression

$$\Gamma = \frac{Z_X - Z_O}{Z_X + Z_O} = \frac{Y_O - Y_X}{Y_O + Y_X} \qquad (6)$$

$$E_r = E_i \Gamma \quad \text{at the load} \qquad (7a)$$

$$I_r = -I_i \Gamma \quad \text{at the load} \qquad (7b)$$

where Z_X and Y_X are the complex load impedance and admittance, and Z_O and Y_O are the characteristic impedance and admittance of the line. ($Y_O = \frac{1}{Z_O}$).

2.3 LINE IMPEDANCE.

2.3.1 VOLTAGE AND CURRENT DISTRIBUTION.

If the line is terminated in an impedance equal to the characteristic impedance of the line, there will be no reflected wave, and $\Gamma = 0$, as indicated by Equation (6). The voltage and current distributions along the line for this case are shown in Figure 3.

If the line is open-circuited at the load, the voltage wave will be completely reflected and will undergo no phase shift on reflection, as indicated by Equation (6), ($Z_X = \infty$), while the current wave will also be completely reflected but will undergo a 180° phase shift on reflection, as shown in Figure 4. If the line is short-circuited, the current and voltage roles are interchanged, and the impedance pattern is shifted $\lambda/4$ along the line. The phase shifts of the voltage and current waves on reflection always differ by 180°, as the reflected wave travels in the opposite direction from the incident wave. A current maximum, therefore, always occurs at a voltage minimum, and vice versa.

The voltage at a maximum of the standing-wave pattern is $|E_i| + |E_r|$ or $|E_i|(1 + |\Gamma|)$ and at a minimum is $|E_i| - |E_r|$ or $|E_i| \times (1 - |\Gamma|)$. The

---

1

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} = \sqrt{\frac{L}{C} \times \frac{1 - j\frac{R}{\omega L}}{1 - j\frac{G}{\omega C}}} \simeq \sqrt{\frac{L}{C}}$$

where L is the inductance per unit length in henrys, C is the capacitance per unit length in farads, R is the series resistance per unit length in ohms, and G is the shunt conductance per unit length in mhos. The approximation is valid when the line losses are low, or when $\frac{R}{L} = \frac{G}{C}$.

ratio of the maximum to minimum voltages, which is called the voltage standing-wave ratio, VSWR, is

$$VSWR = \frac{E_{max}}{E_{min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \qquad (8a)$$

The standing-wave ratio is frequently expressed in decibels.

$$VSWR \text{ in db} = 20 \log_{10} \frac{E_{max}}{E_{min}} \qquad (8b)$$

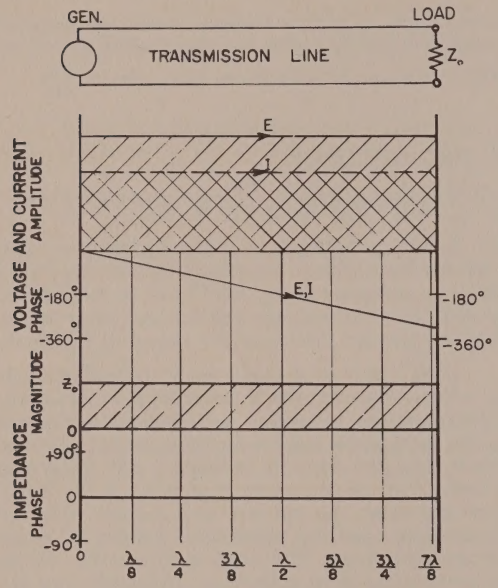


Figure 3. Chart showing voltage and current waves along a transmission line terminated in its characteristic impedance. Note the absence of reflected waves and that the impedance is constant and equal to the characteristic impedance at all points along the line.

At any point along a uniform lossless line, the impedance, Z_p, seen looking towards the load, is the ratio of the complex voltage to the complex current at that point. It varies along the line in a cyclical manner, repeating each half-wavelength of the line, as shown in Figure 4.

At a voltage maximum on the line, the incident and reflected voltage waves are in phase, and the incident and reflected current waves are 180° out of phase with each other. Since the incident voltage and incident current waves are always in phase (assuming Z_o is a pure resistance), the effective voltage and current at the voltage maximum are in phase and the effective impedance at that point is pure resistance. At a voltage maximum, the effective impedance is equal to the characteristic impedance multiplied by the VSWR.

$$R_{p\,max} = Z_o \times (VSWR) \qquad (9a)$$

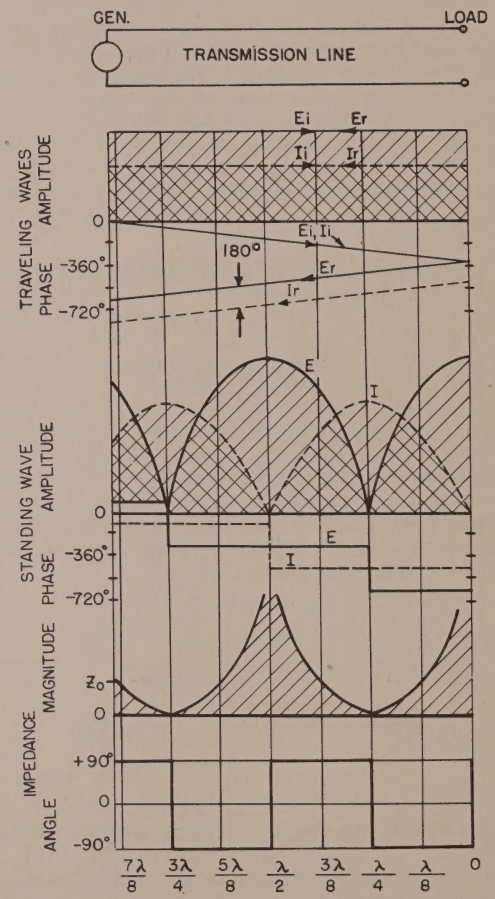


Figure 4. Chart showing voltage and current waves along a transmission line terminated in an open-circuit. Note that the minima of the voltage waves occur at the maxima of the current waves, and vice versa, and that the separation of adjacent minima for each wave is a half-wavelength. The variation in the magnitude and phase angle of the impedance is also shown.

At a voltage minimum, the two voltage waves are opposing and the two current waves are aiding. Again the effective impedance is a pure resistance and is equal to the characteristic impedance of the line divided by the VSWR.

$$R_{p\,min} = \frac{Z_o}{VSWR} \qquad (9b)$$

The impedance, Z_p, at any point along the line is related to the load impedance by the expression

$$Z_p = Z_o \times \frac{Z_x + jZ_o \tan\theta}{Z_o + jZ_x \tan\theta} \qquad (10a)$$

$$Y_p = Y_o \times \frac{Y_x + jY_o \tan\theta}{Y_o + jY_x \tan\theta} \qquad (10b)$$

where Z_x and Y_x are the complex load impedance and admittance, Z_o and Y_o are the characteristic impedance and admittance of the line, and θ is the electrical length of line between the load and the point along the line at which the impedance is measured. (See Figure 5.)[2] The effective length, ℓ_e, is proportional to the physical length, ℓ, multiplied by the square root of the effective dielectric constant, K, of the insulating material between the inner and outer conductors.

$$\ell_e = \ell\sqrt{K} \qquad (11a)$$

$$\theta = \frac{\ell_e}{\lambda} \text{ wavelengths} \qquad (11b)$$

$$\theta = \frac{2\pi\ell}{\lambda}\sqrt{K} \text{ radians} \qquad (11c)$$

$$\theta = \frac{360\ell}{\lambda}\sqrt{K} \text{ degrees} \qquad (11d)$$

If ℓ is in centimeters,

$$\theta = 0.012 f_{Mc}\,\ell\sqrt{K} \text{ degrees} \qquad (11e)$$

2.3.2 DETERMINATION OF THE LOAD IMPEDANCE FROM THE IMPEDANCE AT ANOTHER POINT ON THE LINE.

The load impedance, Z_X, or admittance, Y_X, can be determined if the impedance, Z_p, at any point along a lossless line is known. The expressions relating the impedances are:

$$Z_x = Z_o \times \frac{Z_p - jZ_o \tan\theta}{Z_o - jZ_p \tan\theta} \qquad (12a)$$

$$Y_x = Y_o \times \frac{Y_p - jY_o \tan\theta}{Y_o - jY_p \tan\theta} \qquad (12b)$$

[2] In Figure 5, point p is shown at a voltage minimum. However, Equations (10a) and (10b) are valid for any location of point p on the line.

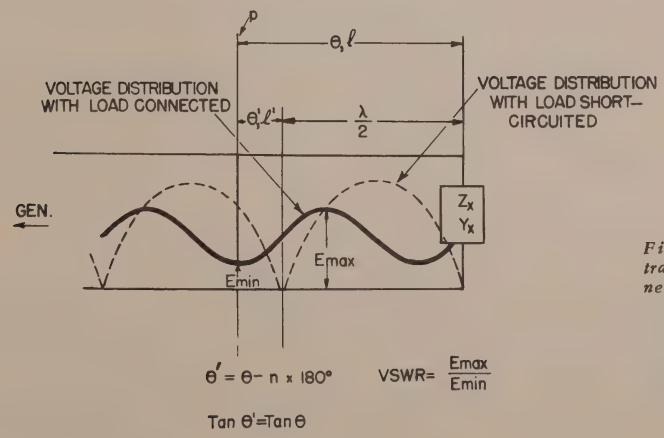


Figure 5. Voltage variation along a transmission line with a load connected and with the line short-circuited at the load.

If the line loss cannot be neglected, the equations are:

$$Z_x = Z_o \times \frac{Z_p - Z_o \tanh\gamma\ell}{Z_o - Z_p \tanh\gamma\ell} \qquad (13a)$$

$$Y_x = Y_o \times \frac{Y_p - Y_o \tanh\gamma\ell}{Y_o - Y_p \tanh\gamma\ell} \qquad (13b)$$

when $\gamma = \alpha + j\beta$, and

α = attenuation constant in nepers/cm

$$= \frac{\text{att. in db/100 ft}}{26940}$$

β = phase constant in radians/cm

$$= 2\pi f\sqrt{LC} = \frac{2\pi\sqrt{K}}{\lambda}$$

2.3.3 DETERMINATION OF THE LOAD IMPEDANCE FROM THE STANDING-WAVE PATTERN.

The load impedance can be calculated from a knowledge of the VSWR present on the line and the position of a voltage minimum with respect to the load, since the impedance at a voltage minimum is related to the VSWR as indicated by Equation (9b). The equation can be combined with Equation (12a) to obtain an expression for the load impedance in terms of the VSWR and the electrical distance, Θ, between the voltage minimum and the load.

$$Z_x = Z_o \times \frac{1 - j(\text{VSWR})\tan\theta}{\text{VSWR} - j\tan\theta} \qquad (14a)$$

$$Z_o \times \frac{2(\text{VSWR}) - j\left[(\text{VSWR})^2 - 1\right]\sin 2\theta}{\left[(\text{VSWR})^2 + 1\right] + \left[(\text{VSWR})^2 - 1\right]\cos 2\theta} \qquad (14b)$$

Since in a lossless line the impedance is the same at half-wavelength intervals along the line, Θ can be the electrical distance between a voltage minimum and any multiple of a half-wavelength from the load (see Figure 5). Of course, if the half-wavelength point used is on the generator side of the voltage minimum located with the load connected, Θ will be negative. The points corresponding to half-wavelength distances from the load can be determined by short-circuiting the line at the load and noting the positions of the voltage minima on the line. The minima will occur at multiples of a half-wavelength from the load.

If the VSWR is greater than 10 tan Θ, the following approximation of Equation (14b) gives good results:

$$R_x \cong \frac{Z_o}{\text{VSWR}\cos^2\theta} \qquad (15a)$$

$$X_x \cong -Z_o \tan\theta \qquad (15b)$$

2.3.4 SMITH CHART.

The calculation of the impedance transformation produced by a length of transmission line using the equations previously presented can be time consuming. Mr. P. H. Smith[3] has devised a chart, shown in Figure 6, which simplifies these calculations. In this chart the circles whose centers lie on the resistance component axis correspond to constant values of resistance. The arcs of circles whose centers lie on an axis perpendicular to the resistance axis correspond to constant values of reactance. The chart covers all values of impedance from zero to infinity. The position of a point corresponding to any given complex impedance can be found from the intersection of the resistance and reactance coordinates corresponding to the resistive and reactive components of the unknown impedance.

As the distance from the load is increased or decreased, the impedance seen looking along the line toward a fixed unknown will travel around a circle with its center at the center of the chart. The angular movement around the circle is proportional to the electrical displacement along the line. One complete traverse of the circle will be made for each half-wavelength of travel. The radius of the circle is a function of the VSWR.

2.3.4.1 Calculation of Impedance at One Point from the Impedance at Another Point on a Line. If the impedance at one point on a line, say at a point p is known, and the impedance at another point a known

[3] Smith, P. H., Electronics, Vol. 17, No. 1, pp. 130-133, 318-325, January 1944.

electrical distance away (for instance, at the load) is desired, the problem can be solved using the Smith Chart in the following manner: First, locate the point on the chart corresponding to the known impedance, as shown in Figure 6. (For example, assume that $Z_p = 20 + j25$ ohms.) Then, draw a line from the center of the chart through Z_p to the outside edge of the chart. If the point at which the impedance is desired is on the load side of the point at which the impedance is known, travel along the WAVELENGTHS TOWARD LOAD scale, from the intersection of the line previously drawn, a distance equal to the electrical distance in wavelengths between the point at which the impedance is known and the point at which it is desired. If the point at which the impedance is desired is on the generator side of the point at which the impedance is known, use the WAVELENGTHS TOWARD GENERATOR scale. (In this example, assume that the electrical distance is 0.11 wavelength toward the load.) Next, draw a circle through Z_p with its center at the center of the chart, or lay out, on the last radial line drawn, a distance equal to the distance between Z_p and the center of the chart. The coordinates of the point found are the resistive and reactive components of the desired impedance. (In the example chosen, the impedance is 16 - j8 ohms.)

The VSWR on the line is a function of the radial distance from the point corresponding to the impedance, to the center of the chart. To find the VSWR, lay out the distance on the STANDING WAVE RATIO scale located at the bottom of the chart, and read the

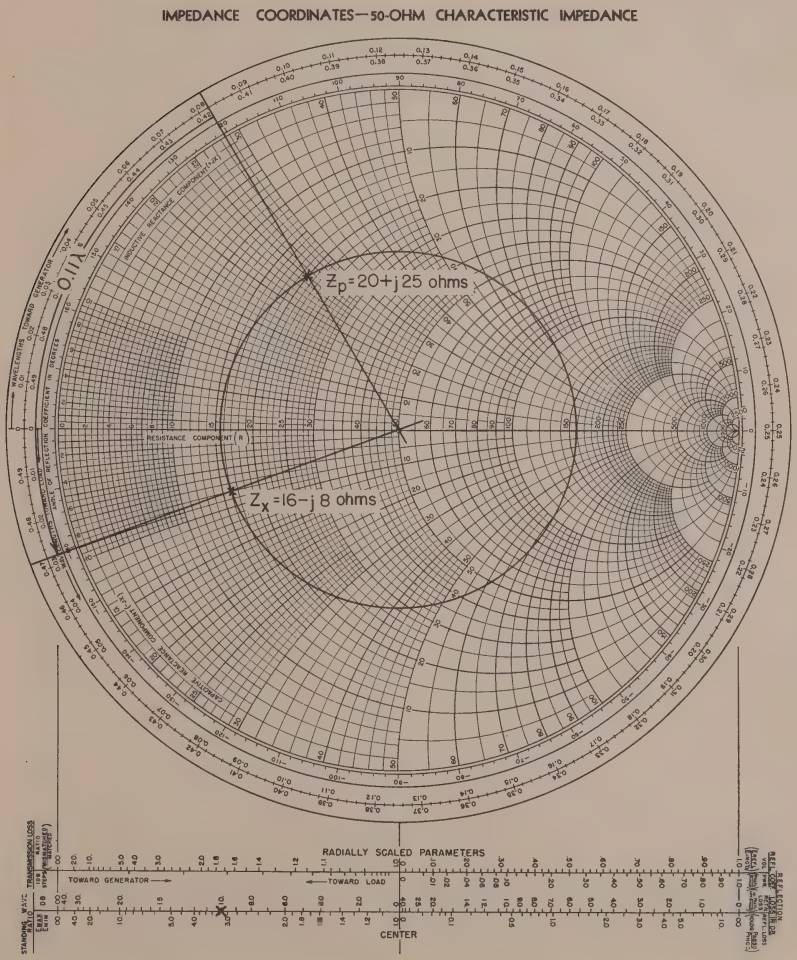


Figure 6. Illustration of the use of the Smith Chart for determining the impedance at a certain point along a line when the impedance a specified electrical distance away is known. In the example plotted, the known impedance, Z_p, is 20 + j25 ohms and the impedance, Z_x, is desired at a point 0.11 wavelength toward the load from the point at which the impedance is known.

VSWR as a ratio, $\frac{Emax}{Emin}$, or in db on the appropriate scale. (In the example of Figure 6, the VSWR is 3.2 or 10.1 db.)

2.3.4.2 Calculation of Impedance at the Load from the VSWR and Position of a Voltage Minimum. In impedance measurements in which the voltage standing-wave pattern is measured, the impedance at a voltage minimum is a pure resistance having a magnitude of $\frac{Z_0}{VSWR}$. Plot this point on the resistance component axis and draw a circle having its center at the center of the chart drawn through the point. The impedance at any point along the transmission line must lie on this circle. To determine the load impedance, travel around the circle from the original point an angular distance on the WAVELENGTHS TOWARD LOAD scale equal to the electrical distance, expressed as a fraction of a wavelength, between the voltage minimum and the load (or a point a half-wavelength away from the load, as explained in Paragraph 2.3.3.) If the half-wave point chosen lies on the generator side of the minimum found with the load connected, travel around the chart in the opposite direction, using the WAVELENGTHS TOWARD GENERATOR scale. The radius of the circle can be determined directly from the VSWR, expressed as a ratio, or, if desired, in decibels by use of the scales labeled STANDING WAVE RATIO, located at the bottom of the chart.

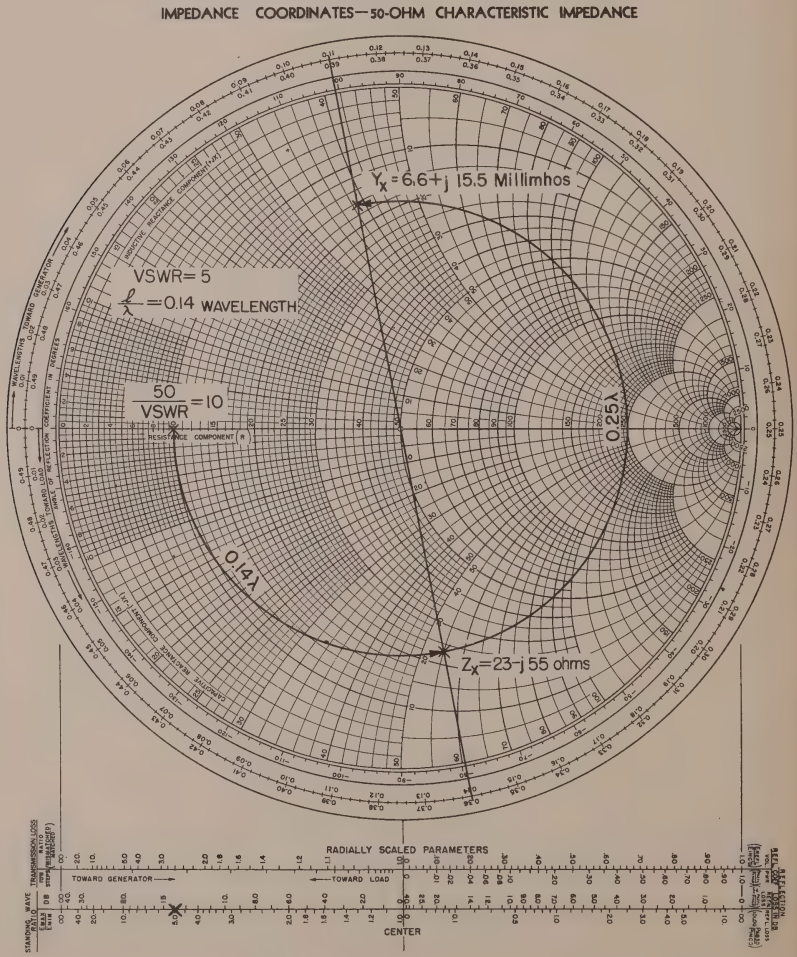


Figure 7. Example of the calculation of the unknown impedance from measurements of the VSWR and position of a voltage minimum, using a Smith Chart. The measured VSWR is 5 and the voltage minimum with the unknown connected is 0.14 wavelength from the effective position of the unknown. A method of determining the admittance of the unknown is also illustrated.

The example plotted on the chart in Figure 7 shows the procedure for determining the load impedance when the VSWR is 5 to 1, and the electrical distance between the load or a half-wavelength point and a voltage minimum is 0.14 wavelength. The unknown impedance, read from the chart, is 23 - j55 ohms.

The Smith Chart can also be used when the line between the load and the measuring point is not lossless. The procedure for correcting for loss is outlined in Paragraph 4.6.2.

NOTE

Additional copies of the Smith Chart are available, drawn for a 50-ohm system in either impedance or admittance coordinates. The Impedance Chart, similar to the one shown in Figure 6 but printed on transparent paper, is Form 756-Z. The Admittance Chart, similar to Figure 8, is Form 756-Y. A normalized chart, with an expanded center portion for low VSWR measurements, is also available on Form 756-NE.

2.3.4.3 Conversion from Impedance to Admittance. The Smith Chart can also be used to obtain the transformation between impedance and admittance. Follow around the circle of constant VSWR a distance of exactly 0.25 wavelength from the impedance point. To obtain the conductance and susceptance in millimhos, simply multiply the coordinates of the newly determined point by 0.4 (see Figure 7). This conversion property is a result of the inversion of impedance every quarter-wavelength along a uniform transmis-

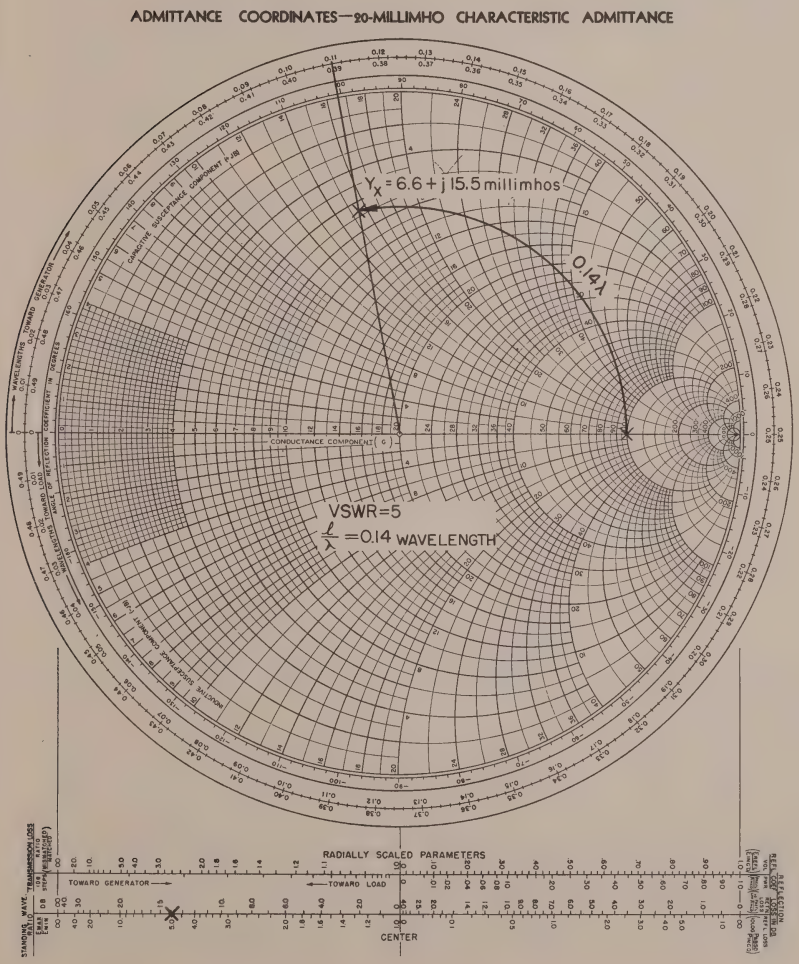


Figure 8. Example of the calculation of the unknown admittance from measurements of the VSWR and the position of a voltage minimum, using the Smith Chart drawn for admittance measurements on lines having characteristic admittances of 20 millimhos (50 ohms).

sion line. The impedances at points 1 and 2, a quarter-wavelength apart, are related by the equation

$$Z_1 = \frac{Z_0^2}{Z_2} \qquad (16a)$$

or

$$Z_1 = Z_0^2 Y_2 \qquad (16b)$$

2.3.4.4 Admittance Measurements Using the Smith Chart. The admittance of the unknown can be obtained directly from a normalized Smith Chart, or from the chart shown in Figure 8, whose coordinates are admittance components, rather than by the procedure outlined in Paragraph 2.3.4.3. When the chart shown in Figure 8 is used, the characteristic admittance, 20 millimhos, is multiplied by the measured VSWR to find the conductance at the voltage minimum. The radius of the corresponding admittance circle on the chart can be found by plotting the measured conductance directly on the conductance axis. The radius can also be found from the STANDING WAVE RATIO scale located at the bottom of the chart. The electrical distance to the load is found and laid off on the WAVELENGTHS TOWARD LOAD scale, starting at 0.25 wavelength. On the VSWR circle, the coordinates of the point corresponding to the angle found on the WAVELENGTHS scale are the values of conductance and susceptance of the unknown.

The example plotted on the chart is the same as that used for the impedance example of Figure 7.

2.3.4.5 Use of Other Forms of the Smith Chart. In some forms of the Smith Chart, all components are normalized with respect to the characteristic impedance to make the chart more adaptable to all values of characteristic impedance lines. If normalized charts are used, the resistance component value used for the voltage-minimum resistance is $\frac{1}{\text{VSWR}}$. and the unknown impedance coordinates obtained must be multiplied by the characteristic impedance of the line to obtain the unknown impedance in ohms. If the admittance is desired, the coordinates that correspond to the admittance should be multiplied by the characteristic admittance.

The normalized Smith Chart is produced in a slide rule form by the Emeloid Corporation, Hillside, New Jersey.

SECTION **3**

DESCRIPTION

3.1 SLOTTED LINE DESIGN.

The Type 874-LBA Slotted Line is designed to measure the voltage standing-wave pattern produced by any load connected to it. Its characteristic impedance is 50 ohms. The outer conductor is slotted for a length of approximately 50 centimeters, and a small shielded probe extends into the region between the two conductors. The probe is mounted on a carriage, which slides along the outside of the outer conductor. The penetration of the probe into the line and, hence, the capacitive coupling between the probe and the line, can be adjusted over a wide range by means of a screw adjustment. Cross-sectional views of the probe arrangement are shown in Figure 9a.

Since the probe is capacitively coupled to the line, the voltage induced in the probe circuit is proportional to the voltage existing between the inner and outer conductors of the line at the probe position.

The carriage is driven by means of a nylon cord which passes around a drum mounted on the casting at one end of the line and around an idler pulley which is mounted on the casting at the other end of the line. The driving knob is attached to the same shaft as the drum. The drive depends upon friction. One and a half turns of the cord around the drum is sufficient to give a positive drive. A ratchet-type take-up reel is located on the back of the carriage to

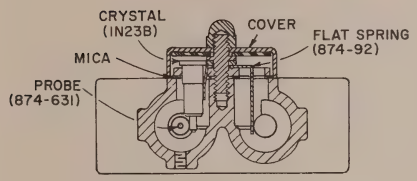
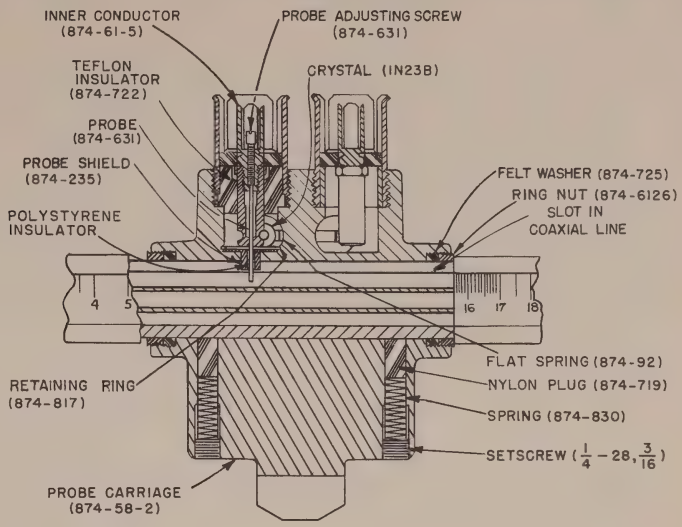


Figure 9a. Cross-sectional views of the carriage on the Type 874-LBA Slotted Line, showing the crystal mount and the adjustable probe.



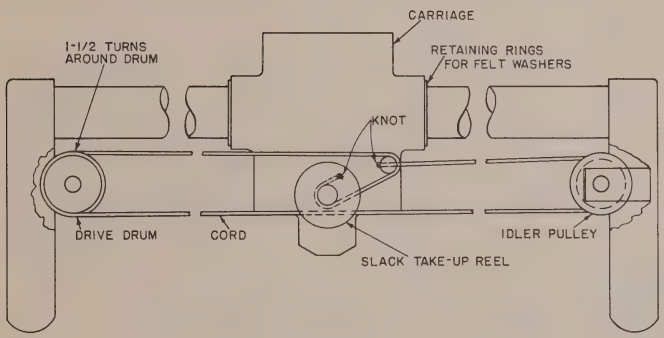


Figure 9b. Rear view of the drive mechanism, showing the arrangement of the nylon cord.

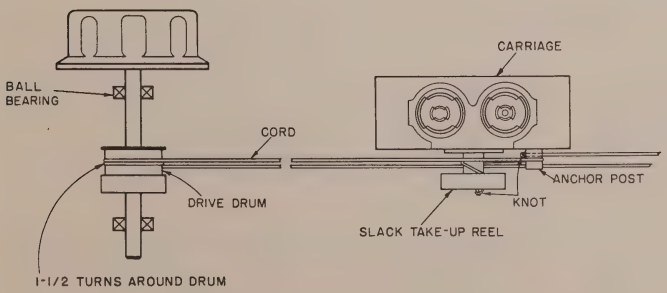


Figure 9c. Installation of the nylon cord, viewed from the top of carriage.

permit adjustment of the cord tension. Figures 9b and 9c show the cord, drum, and take-up device.

The rf voltage induced in the probe can be measured by means of a built-in tuned crystal detector and associated indicating equipment, as shown in Figures 10 and 11, or by means of an external receiver, as shown in Figure 12.

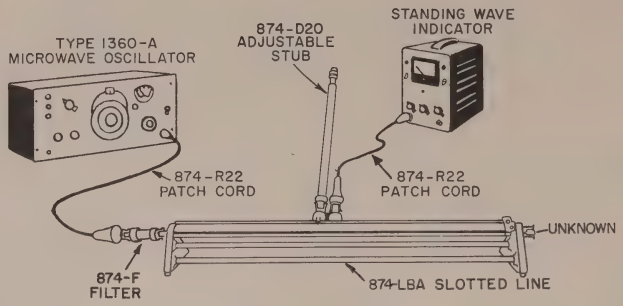


Figure 10. Use of a modulated source for measurements with the Type 874-LBA Slotted Line. The built-in crystal detector and a standing-wave indicator are used to detect the voltage induced in the probe. The probe is tuned by means of the adjustable stub shown.

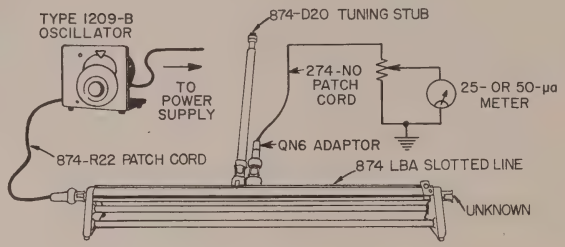


Figure 11. Use of an unmodulated source for measurements with the Type 874-LBA Slotted Line. The indicator is a microammeter.

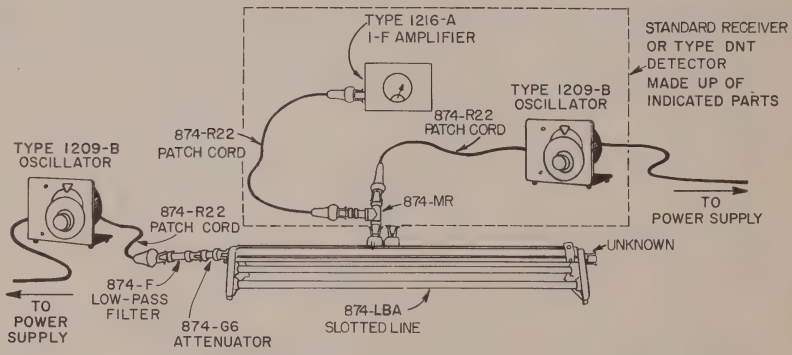


Figure 12. Use of an unmodulated source and a superheterodyne detector or receiver for measurements with the Type 874-LBA Slotted Line.

One end of the slotted line is terminated in the circuit under test, usually called the unknown, and the other in the power source. Each end is fitted with a Type 874 Connector which introduces only a very small reflected wave in the line, at frequencies up to about 7000 Mc.

3.2 GENERATOR.

The generator requirements are dependent on the type of detector used and on the standing-wave ratio of the load to be measured. Table I is a chart showing several possible generators with their respective frequency ranges.

3.3 DETECTOR.

As mentioned previously, either the built-in crystal detector[4] or an external receiver can be used as a detector.

3.3.1 CRYSTAL RECTIFIER AND STANDING-WAVE METER.

The most commonly used and the most generally satisfactory detector is the built-in crystal recti-

[4] If desired, Type 610-A Bolometer elements, manufactured by Polytechnic Research and Development Co., can be inserted in place of the crystal.

TABLE 1. GENERATORS

Type	Name	Frequency Range
1215-B	Unit Oscillator	50-250 Mc
1209-B	Unit Oscillator	250-960 Mc
1209-BL	Unit Oscillator	180-600 Mc
1208-B	Unit Oscillator	65-500 Mc
1361-A	UHF Oscillator	500-1000 Mc
1218-A	Unit Oscillator	900-2000 Mc
1360-A	Klystron Oscillator	1.7-4.0 Mc

fier, with one of the several commercially available VSWR indicators. The oscillator driving the line should be modulated, preferably by square waves. The Type 1232-A Tuned Amplifier and Null Detector is a satisfactory standing-wave indicator when the VSWR or the unknown is less than 1.8.

At very low levels, the crystal operates in the square-law region; that is, the rectified output is proportional to the square of the rf input. At high levels the crystal approaches a linear characteristic. In most cases, the crystal is operated in the square-law range. To check for square-law operation, measure the same unknown at different detector-signal levels, or compare the measured shape of the standing-wave pattern on a short-circuited line with that of a sine wave whose period is $\lambda/2$.

3.3.2 OTHER DETECTORS.

3.3.2.1 Crystal Rectifier and Microammeter. An even simpler detector system consists of the built-in crystal rectifier used with an external microammeter, as shown in Figure 11. In this case, the rectified dc output of the crystal is measured on a sensitive microammeter connected between the inner and outer terminals of the right-hand connector on the probe carriage. In most cases, the rectified dc output is closely proportional to the square of the rf input at currents up to roughly 50 microamperes. The limit of the square-law region is greatly affected by the resistance of the microammeter, since the rf crystal impedance varies with the dc bias voltage developed across the meter. Therefore, for the most accurate results, the detector characteristic should be checked at the operating frequency, using an rf attenuator. The sensitivity of this system is poor, and difficulties are usually encountered in measuring even a moderately high VSWR unless the oscillator output is large, as the probe coupling required may be excessive (refer to Paragraph 4.3). The simplicity of the system makes it attractive in many cases when a low VSWR is to be measured.

The detector can be used beyond its square-law range if it is calibrated in terms of an rf attenuator used to control accurately the relative input to the line, or by the actual adjustment of the rf input at the voltage maximum and at the voltage minimum to produce the same meter indication. In the second method, the VSWR can be read from the rf attenuator, and all dependence on the detector response is then eliminated. For measurements on lines carrying high power, a 25k-ohm potentiometer can be used as shown in Figure 11. In those cases, operation is usually beyond the square-law region and is often at a high enough level to be in the linear range.

3.3.2.2 Heterodyne Detector. The Type DNT Detector (See Figure 12), which consists of the Type 874-MR Mixer Rectifier, the Type 1216-A Unit I-F Amplifier, and a Unit Oscillator for heterodyning the signal, is also a satisfactory detector for the slotted line, particularly for the measurement of high VSWR's, because of its good sensitivity and harmonic rejection. The shielding of this detector is excellent, a property which is useful in the measurement of radiating systems. Harmonics of the local oscillator frequency can be used to beat with the signal from the slotted line. Hence, the upper frequency limit may be several times the upper frequency limit of the oscillator.

SECTION **4**

OPERATION

4.1 CONNECTIONS AND ADJUSTMENTS.

4.1.1 GENERAL.

In use, the slotted line is fed from an oscillator which is connected to one end of the line. The circuit to be measured is connected to the other end. If a Type 874-MR Mixer Rectifier (Paragraph 3.3.2.2) is to be used as the detector, it is mounted directly on the left-hand connector on the probe carriage, as indicated in Figure 12. No connection is made to the other connector on the carriage. If a receiver is to be used as a detector, a length of double-shielded cable fitted with coaxial connectors should be used to connect the left-hand connector on the carriage to the receiver input. A Type 874-R20 or -R22 Patch Cord is suitable.

If the built-in crystal detector (refer to Paragraphs 3.3.1 and 3.3.2) is to be used, a Type 874-D20 Adjustable Stub should be inserted in the left-hand connector on the carriage. The shielded connection to the amplifier, attenuator, or microammeter should be made from the other connector using a Type 874-R22 Patch Cord, as shown in Figure 10, or a Type 274-NO Patch Cord with a Type 874-QN6 Adaptor, as shown in Figure 11.

4.1.2 COAXIAL ADAPTORS.

If the unknown, the generator, or the detector is fitted with connectors other than the Type 874, adaptors can be used to make the necessary transition to the Type 874 Connector. A large number of adaptors are available (see list at the rear of this manual), permitting use of the slotted line with most standard connectors. The low standing-wave ratios of the Type 874-Q Adaptors assure a minimum of reflection, and the adaptors will have no significant effect on the measurements. Any of the connectors listed in the table of adaptors may be used. It should be remembered, however, that the impedance of Type UHF Connectors is not constant with frequency and may introduce appreciable reflection in the line at higher frequencies.

In addition to the adaptors, there are available Type 874 tees, ells, air lines, rotary joints, and other accessories for convenience of connection. Refer to the list at the rear of this manual or, for full description, to the latest General Radio Catalog.

4.1.3 METHODS OF SHORT- AND OPEN-CIRCUITING A LINE.

The method of producing the short-circuit for the line-length measurement or adjustment is important. When an antenna or other element terminating a line is measured, the short circuit can be made by wrapping a piece of copper foil around the inner conductor. Then bind it to the outer conductor of the feed line at its end, as shown in Figure 13c.

An accurately positioned open-circuit is more difficult to obtain than an accurately positioned short-circuit, as the fringing capacitance at the end of the center conductor will effectively make the line appear to be longer than it really is. Compensation for the fringing capacitance is provided in the open-circuit termination units mentioned below.

A more satisfactory method of producing a short-circuit or open-circuit is to use a Type 874-WN or WN3 Short-Circuit Termination or Type 874-WO or WO3 Open-Circuit Termination Unit. The Types WN3 and WO3 Units produce a short- or open-circuit at a physical distance of 3 cm (3.2 cm electrical distance) from the front face, on the measuring instrument side of the insulating bead, as shown in Figure 13. The front face of the bead is located at the bottom of the slots between the contacts on the outer connector. Hence its position can be easily determined from the outside of the connector. If the device under test is fitted with a Type 874-B Connector and a length of 50-ohm Air Line, the circuit under test can be disconnected and a Type 874-WN3 or Type 874-WO3 Short- or Open-Circuit Termination Unit connected for the line-length measurement. The coaxial-line section of a Type 874-M Component Mount can be used for this purpose, or a Type 874-WN3 Short Circuit or a Type 874-L10 Air Line can be modified to be suitable. The physical distance of the air line between the front face of the insulating bead and the point at which the measurement is to be made must be exactly 3 cm. This arrangement produces very accurate results.

The Type 874-WN or -WO Termination Unit produces a short or open circuit directly at the front face of the insulating bead. These units can be used, even if the impedance is desired at a point on the line other than at the face of the bead, if the electrical

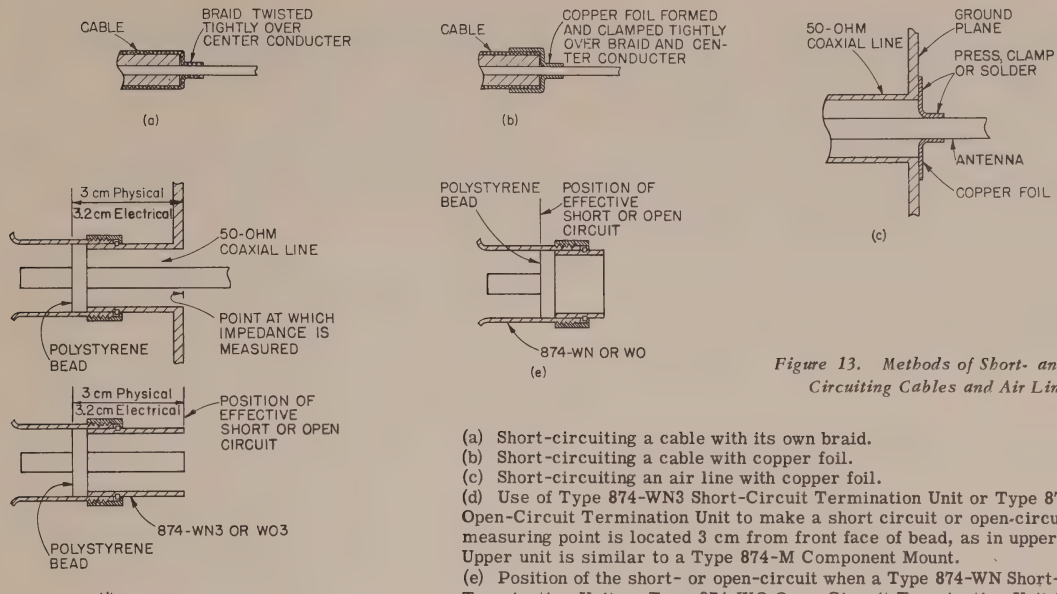


Figure 13. Methods of Short- and Open-Circuiting Cables and Air Lines.

(a) Short-circuiting a cable with its own braid.
(b) Short-circuiting a cable with copper foil.
(c) Short-circuiting an air line with copper foil.
(d) Use of Type 874-WN3 Short-Circuit Termination Unit or Type 874-WO3 Open-Circuit Termination Unit to make a short circuit or open-circuit when measuring point is located 3 cm from front face of bead, as in upper figure. Upper unit is similar to a Type 874-M Component Mount.
(e) Position of the short- or open-circuit when a Type 874-WN Short-Circuit Termination Unit or Type 874-WO Open-Circuit Termination Unit is used.

distance between the two points is added to or subtracted from the line length measured with the short- or open-circuit termination unit connected. The electrical line length for air dielectric line is equal to the physical length. Each bead in the Type 874 Connector has an electrical length of 0.55 cm.

To determine the impedance at the input to a coaxial circuit connected to the slotted line, a Type 874-WN Short-Circuit can be used to produce a short circuit directly at the front face of the insulating bead in the Type 874 Connector on the circuit under test. (The front face of the bead is located at the bottom of the slots in the outer connector.)

4.2 DETECTOR TUNING.

4.2.1 CRYSTAL RECTIFIER TUNING.

The crystal rectifier built into the carriage is tuned by means of the adjustable stub, which is effectively connected in parallel with it in order to increase the sensitivity and to provide selectivity. The stub is adjusted until maximum output is indicated by the detector.

Be sure the stub is not tuned to a harmonic of the desired signal rather than to the fundamental. Confusion may result in some cases if the tuning is done with a high VSWR on the line, as the minima of the harmonics may not be coincident with the minima of the fundamental and, consequently, the harmonic content of the signal picked up by the probe may be several orders of magnitude greater than that present in the local oscillator output. To minimize the possibility of mistuning, the probe should be tuned with a low VSWR on the line, for instance, with the line terminated in a Type 874-WM Termination Unit or with the load end of the slotted line open-circuited. In the latter case, the minima of the harmonics fall very close to the fundamental minima. Hence, the possibility of confusion is small, even though the VSWR is high. As a check, the distance between two adjacent voltage minima on the line can be measured. If the stub is tuned correctly, the spacing should be half a wavelength.

With the Type 874-D20 Adjustable Stub, the crystal can be tuned to frequencies from about 275 Mc to above 5000 Mc. In the vicinity of 3000 Mc the crystal is self-resonant; the effective Q of the probe circuit is low and the tuning rather broad. For operation at frequencies below 275 Mc, a Type 874-D50 Adjustable Stub can be used down to 150 Mc, or various lengths of Type 874-L Air Line can be inserted in series with the adjustable stub. Smoother carriage operation is obtained when the low-frequency stub is used if the line is tilted forward slightly, making the stub stand more nearly vertical.

4.2.2 HETERODYNE DETECTOR.

When the DNT Detector is used, care must be taken to tune the local oscillator to beat with the desired signal and not with one of its harmonics. Harmonics of the oscillator signal can beat with harmonics of the signal picked up from the slotted line and produce an output at the intermediate frequency if the local oscillator is tuned to a wrong frequency. Proper settings of the local oscillator are given by the following expression, assuming that the intermediate frequency is 30 Mc.

$$f_{LO} = \frac{f_S \pm 30}{n} \qquad (17)$$

where f_{LO} is the frequency of the local oscillator, f_S is the signal frequency, and n is an integer, corresponding to the harmonic of the local oscillator signal used. Always use the lowest possible harmonic.

If n = 1, there are two possible settings of the local oscillator separated by 60 megacycles and centered about the signal frequency. If n = 2, the two possible settings are separated by 30 Mc and are centered about f_S/n. In the general case, the two possible settings are separated by 60/n and are centered about the frequency f_S/n.

The second harmonic of the desired signal frequency will produce a beat frequency of 30 Mc when the local oscillator frequency is

$$f_{LO} = \frac{2f_S \pm 30}{n} = \frac{f_S \pm 15}{n/2} \qquad (18)$$

or, in general,

$$f_{LO} = \frac{f_S \pm \frac{30}{h}}{\frac{n}{h}} \qquad (19)$$

where h is the harmonic of the signal frequency. It can be seen from the above equation that some of the harmonic responses may be located reasonably close to the frequency at which the fundamental is detected. The higher the harmonic of the local oscillator, the closer will be the spurious responses.

In general, spurious responses do not cause much difficulty, as the frequency to which the detector is tuned can be easily checked by measuring the distance between two voltage minima on the line, which should be half a wavelength at the operating frequency. The use of an appropriate Type 874-F Low-Pass Filter is often convenient in these cases.

At some frequencies it is necessary to insert a Type 874-L10, 10-cm Air Line between the connector on the carriage and the mixer rectifier, in order to develop sufficient local-oscillator voltage across the crystal.

4.3 PROBE PENETRATION ADJUSTMENT.

The probe penetration should be adjusted for adaquate sensitivity as well as insignificant effect on the measured VSWR. The presence of the probe affects the VSWR because it is a small admittance in shunt with the line. It has the greatest effect at a voltage maximum, where the line impedance is high.

To adjust the probe penetration, remove the tuning stub connected to the left-hand connector and turn the small screw found inside the inner connector. (See Figure 9.) Clockwise rotation of the screw increases the coupling. In most cases in which moderate VSWR's are measured, a penetration of about 30% of the distance between the two conductors gives satisfactory results. To adjust the coupling to 30%, increase the coupling until the probe strikes the center conductor of the slotted line; then back it off six full turns of the screw. The point of contact between the probe and the center conductor is most easily measured by connecting an ohmmeter between the inner and outer conductors of the line. Note the point at which the resistance suddenly drops from a very high value to a reasonably low value. The crystal is in series with this circuit, so the resistance will not drop to zero. No indication will be obtained if the crystal has been removed. Do not screw the probe down tight against the center conductor, as it will damage the probe.

The amount of probe penetration can be visually checked by looking at the probe through the slot from one end of the line.

The effect of the probe coupling on the VSWR can be determined by measurement of the VSWR at two different degrees of coupling. If the measured VSWR is the same in both cases, the probe coupling used has no significant effect on the measurement. If the measured VSWR's are different, additional measurement should be made with decreasing amounts of probe penetration until no difference occurs. However, as pointed out in the previous paragraph, a 30% coupling usually gives satisfactory results except when the VSWR is high, which usually requires a larger coupling.

The probe coupling or the oscillator output should be adjusted until the output from the detector is in a satisfactory range. If the crystal detector is used, this means the maximum output to be measured should not correspond to an input beyond the square-law range if the square-law characteristic is to be depended upon (refer to Paragraph 3.3.1), and the probe coupling should not be large enough to affect the measurements appreciably.

The variation in probe coupling along the line is affected by the depth of penetration. At large penetrations the variation tends to increase. The specified ± 1-1/2% holds for penetrations of 30%.

4.4 MEASUREMENT OF WAVELENGTH.

The wavelength of the exciting wave in air can be measured using the slotted line by observing the separation between adjacent voltage minima when the line is short- or open-circuited. As explained in Paragraph 2.2, the spacing between adjacent minima, d, is one-half wavelength or

$$\lambda = 2d \qquad (20)$$

For greater accuracy at the higher frequencies, the distance over a span of several minima can be measured. If the number of minima spanned, not counting the starting point, is n, then

$$\lambda = \frac{2d}{n} \qquad (21)$$

4.5 MEASUREMENT OF LOW VSWR (BELOW 10:1).

4.5.1 TWO METHODS.

When the standing-wave ratio to be measured is less than about 10:1, the VSWR can be read directly on the scale of a standing-wave indicator (follow the manufacturer's instructions); or, with the Type 1232-A Tuned Amplifier and Null Detector or the Type DNT Detector, it can be determined from the difference between the two decibel-scale readings corresponding to the voltage maximum and voltage minimum on the slotted line.

The db difference can be converted to VSWR on the auxiliary scales at the bottom of the Smith Chart or can be computed from the expression

$$\text{VSWR} = \log^{-1} \frac{\text{db}}{20}.$$

When using the Type 1232-A Amplifier with a square-law detector, the difference in db must be divided by two to obtain the value to use in the above formula.

The probe coupling can vary a maximum of ± 1-1/2% along the line, and the VSWR measured is in error by the difference in coupling coefficients at the maximum and minimum voltage points. This error can be avoided by calibration of the variation of coupling with probe position, as outlined in Paragraph 5.2, or it can be reduced greatly by measuring several minima and several maxima, then averaging the results. The coupling usually changes the most near the ends of the line and, hence, better accuracy usually can be obtained if measurements close to either end are avoided.

For a particular setup, a check must be made to determine whether the crystal is operating in the square-law range. (Refer to Paragraph 3.3.1.)

4.5.2 DETERMINATION OF IMPEDANCE FROM VSWR.

To determine the impedance of the unknown, the VSWR and the electrical distance between a voltage minimum on the line and the unknown must be determined. The unknown impedance is calculated as outlined in Paragraph 2.3.3 or 2.3.4.

To find the effective distance to the unknown, short-circuit the line with a very-low-inductance short at the position of the unknown (refer to Paragraph 4.1.3) and measure the position of a voltage minimum on the line. This minimum is an integral number of half-wavelengths from the unknown. Since the impedance along a lossless line is the same every half-wavelength, the position of the voltage minimum found with the line short-circuited is the effective position of the unknown. If the line is very long, oscillator frequency shifts (discussed in Paragraph 4.6.3) may be serious. See Figure 5.

4.5.3 BROAD MINIMUM.

When the VSWR is very low, the minima will be very broad, and it may be difficult to locate their positions accurately. In this case, better results usually can be obtained by measuring the positions of points on either side of a voltage minimum at which the voltage is roughly the mean of the minimum and maximum voltages, as shown in Figure 14. The minimum is located midway between these two points. (Either the geometric or the arithmetical mean can be used. It is necessary only to have an identifiable value.)

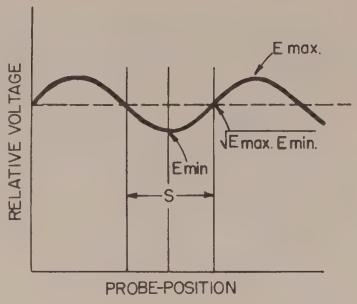


Figure 14. Method of improving the accuracy of the determination of the position of a voltage minimum on the line when the VSWR is low.

4.5.4 ADDITIONAL PRECAUTIONS.

If the line connecting the unknown to the slotted line has a significant amount of loss, the effect of the loss on the unknown impedance can be corrected for, as outlined in Paragraph 4.6.2

Harmonics of the oscillator frequency may also cause trouble, as discussed in Paragraph 4.6.4. The effect will tend to be most serious when the VSWR at the harmonic frequencies is high.

4.6 MEASUREMENT OF HIGH VSWR.

4.6.1 LIMITATIONS.

When the VSWR on the line is 10 to 1 or more, direct accurate measurements of a voltage maximum and a voltage minimum are difficult because:

(1) The effect of a fixed probe-coupling coefficient on the measurement increases as the VSWR increases because the line impedance at the voltage maximum increases, and the shunt impedance produced by the probe has greater effect.

(2) As the VSWR increases, the voltage at the voltage minimum usually decreases and, hence, a greater probe-coupling coefficient is required to obtain adequate sensitivity. The increased probe coupling may cause errors as outlined in (1).

(3) The accuracy of the measurement of the relative voltage decreases as the VSWR increases. The voltage range becomes too great to permit operation entirely in the square-law region.

4.6.2 WIDTH OF MINIMUM METHOD.

Accurate measurements of VSWR's greater than 10 can be made using the width-of-minimum method. This is analogous to the determination of circuit Q by measurement of the frequency increment between the two half-power points. In the slotted line case, the spacing, Δ, between points on the line at which the rf voltage is $\sqrt{2}$ times the voltage at the minimum, is measured, as shown in Figure 15. The VSWR is related to the spacing, Δ, and the wavelength, λ, by the expression

$$\text{VSWR} \cong \frac{\lambda}{\pi\Delta} \qquad (22)$$

If the detector is operating in the square-law region, $\sqrt{2}$ times the rf voltage corresponds to twice the minimum rectified output or a 6-db change in output.

For very sharp minima, the width of the minimum can be measured to a much greater accuracy by use of the Type 874-LV Micrometer Vernier than by means of the centimeter scale on the slotted line. The vernier can be read to ±0.002 cm. When the vernier is used, the probe is moved slightly to the right of the minimum and the vernier is adjusted to have its plunger strike the carriage on the unpainted surface below the output connector. To adjust the position of the vernier, loosen the thumbscrew which clamps the vernier to a reinforcing rod, slide it along to the proper position, and relock it.

Then drive the probe through the minimum and the twice-power points by turning the micrometer screw. Determine the output meter reading corresponding to the minimum; set the standing-wave indicator for 6 db more attenuation.

Back off the micrometer and return the probe to the right side of the minimum. Then again drive the probe through the minimum and twice-power points and note the two micrometer readings corresponding to the original output meter reading. The difference between these readings is equal to Δ.

If the minimum is too close to the right-hand end of the line to permit the use of the vernier in the usual manner, the vernier can be moved to the left-hand side of the carriage and the other end of the plunger can be used to drive the carriage.

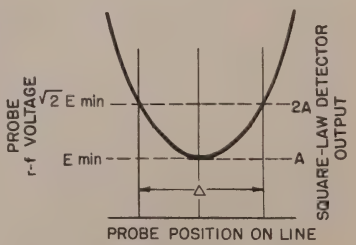


Figure 15. Method of measuring the width of the voltage minimum for VSWR determinations when the VSWR is high.

The electrical distance between the unknown and the minimum found on the line can be determined as outlined in Paragraph 4.5.2.

At very high standing-wave ratios, the losses in the slotted line and in any connecting line or cable used can have an appreciable effect on the measurements. To keep this error as low as possible, the voltage minimum nearest the load should be measured. A correction for the loss in the line can be made as outlined in Paragraph 4.6.3.

4.6.3 CORRECTION FOR LOSS IN LINE BETWEEN MEASURING POINT AND UNKNOWN.

When a load is connected to the slotted line through a length of air line or cable, the loss in the air line or cable may appreciably affect the measurements. Loss in the cable tends to make the measured VSWR less than the true VSWR produced by the load.

The amount of loss in a length of cable can be estimated from published data or can be measured on the slotted line. Determine the VSWR with the load end of the connecting line or cable open-circuited and shielded to prevent radiation losses. An open circuit is used for this measurement to eliminate the significant losses present in most short-circuiting devices. A Type 874-WO Open-Circuit Termination is useful for this purpose. The total attenuation, $\alpha\ell$, in the length of cable is:

$$\tanh \alpha\ell = \frac{1}{(VSWR)_{oc}} \qquad (23a)$$

$$\alpha\ell = \tanh^{-1} \frac{1}{(VSWR)_{oc}} \text{ nepers} \qquad (23b)$$

$$= 8.686 \tanh^{-1} \frac{1}{(VSWR)_{oc}} \text{ db.} \qquad (23c)$$

where the VSWR is expressed as a ratio, not in db.

If the VSWR is greater than 10, the tanh is closely equal to the angle, and

$$\alpha\ell \cong \frac{1}{(VSWR)_{oc}} \text{ nepers} \qquad (24)$$

$$= \frac{8.686}{(VSWR)_{oc}} \text{ db.}$$

The attenuation can also be determined from the open-circuited VSWR by use of the TRANSMISSION LOSS and STANDING WAVE RATIO scales located below the Smith Chart, shown in Figure 16b. The point corresponding to the open circuit VSWR is located on the $\frac{E_{max}}{E_{min}}$ or DB scales under STANDING WAVE RATIO. At the same distance from the center, find a corresponding point on the TRANSMISSION LOSS scale. Attenuation of the line is equal to the number of decibels between the left-hand end of the scale labeled 1 DB STEPS and this latter point.

In most cases the loss in the slotted line itself can be neglected, but the loss in the line or cable used to connect the slotted line and the load is of importance. The unknown impedance can then be calculated in the same manner as for the lossless case, if the measured voltage standing-wave ratio, $(VSWR)_m$, is first corrected for the effect of the loss in the line. The effective voltage standing-wave ratio, $(VSWR)_e$, is then exactly

$$(VSWR)_e = \frac{(VSWR)_m - \frac{1}{(VSWR)_{oc}}}{1 - \frac{(VSWR)_m}{(VSWR)_{oc}}} \qquad (25)$$

4.6.4 CORRECTION FOR LUMPED SERIES RESISTANCE AT CONNECTOR.

In the measurement of a very high VSWR, the lumped resistance loss at the Type 874 Connector on the slotted line can have an important effect. The

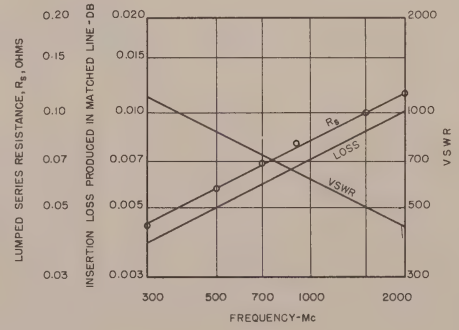


Figure 16a. Plot of the effective lumped series resistance at the connector, measured on a typical Type 874-LBA Slotted Line. The insertion-loss produced in a matched line by the measured value of lumped resistance is also indicated, as well as the VSWR which would be produced by the measured lumped resistance located at a current maximum in an open- or short-circuited 50-ohm line that has no other losses.

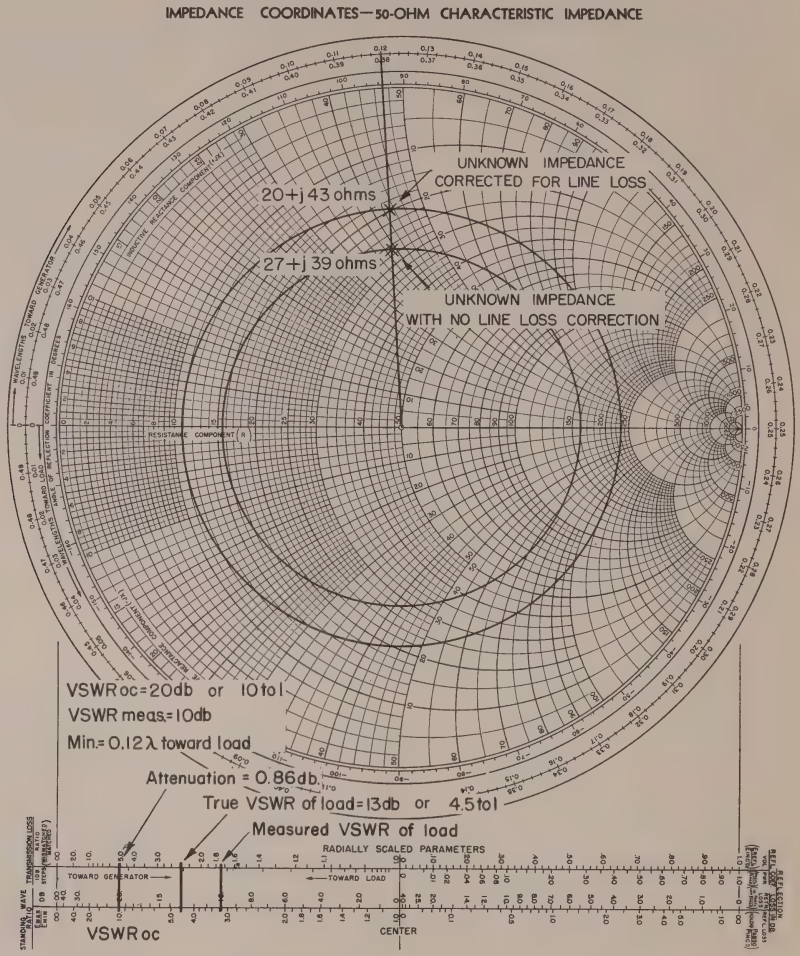


Figure 16b. Example of the use of the Smith Chart for line length corrections when the line has an appreciable amount of loss. (See Paragraph 4.6.3.)

magnitude of this resistance for a typical line is plotted in Figure 16a. Maximum error in measured VSWR occurs when the voltage maximum is at the effective position of the series resistance. If a current minimum occurs at this point, there is no error. This should be borne in mind when corrections for line loss are determined (refer to Paragraph 4.6.3). When the position of the standing-wave pattern is different for the measurement with unknown connected from its position with unknown disconnected, the lumped resistance loss may be different in the two measurements.

This type of error can be avoided by use of the substitution method of measurement. In this method, the reactance at the end of the line is adjusted with the unknown disconnected to produce a voltage minimum at exactly the same position on the slotted line as produced with the unknown connected. The effective loss produced by the lumped resistance is the same in both cases; hence Equation 26 can be used to obtain the true value of the VSWR produced by the unknown alone.

$$\frac{1}{(\mathrm{VSWR})_e} \cong \frac{1}{(\mathrm{VSWR})_m} - \frac{1}{(\mathrm{VSWR})_{oc}}$$

$$(\mathrm{VSWR})_e \cong \frac{(\mathrm{VSWR})_m}{1 - \frac{(\mathrm{VSWR})_m}{(\mathrm{VSWR})_{oc}}} \qquad (26)$$

The impedance of an unknown connected to the slotted line by a line or cable having an appreciable loss can be calculated from the slotted-line measurements by use of the Smith Chart exactly as outlined in Paragraph 2.3.4.2 if the measured VSWR is corrected as indicated in Equation (25); or the complete correction procedure can be carried out on the Smith Chart and the need for the solution of Equation (25) eliminated in the following manner. First, the point corresponding to the measured VSWR is determined on the scale marked STANDING WAVE RATIO, located below the chart, and the corresponding point on the TRANSMISSION LOSS, 1 DB STEPS scale is found. Travel outward on this scale TOWARD LOAD, a distance corresponding to the db attenuation in the line and locate a new point. The radius of the circle drawn on the Smith Chart is the distance from this point to the center of the scale. The unknown impedance is found on this new circle at an angle from the resistance axis corresponding to the electrical distance to the load, as outlined in Paragraph 2.3.4.2.

For example, suppose the measured open-circuit VSWR is 20 db, the VSWR with the load connected is 10 db, and the minimum with the load connected is 0.12 wavelength on the load side of the short-circuit minimum. The attenuation, $\alpha\ell$, in the length of cable is 0.86 db. The point on the STANDING WAVE RATIO scale for a VSWR of 10 db is located as shown in Figure 16b, and the corresponding point is found on the TRANSMISSION LOSS 1-DB STEPS scale. A new point on the TRANSMISSION LOSS scale 0.86 db (0.86 division) toward the left-hand end of the scale is found and a line is drawn from this point to the STANDING WAVE RATIO scale. The reading of the scale at this point is 4.5 or 13 db, which is the true VSWR.

Corrections for line length can also be made by use of the following transmission-line equations, from Equations (14a) and (14b):

$$R_x = Z_0 \times \frac{2(VSWR)_e}{\left[(VSWR)_e^2 + 1\right] + \left[(VSWR)_e^2 - 1\right]\cos 2\theta} \qquad (27)$$

$$X_x = -Z_0 \times \frac{\left[(VSWR)_e^2 - 1\right]\sin 2\theta}{\left[(VSWR)_e^2 + 1\right] + \left[(VSWR)_e^2 - 1\right]\cos 2\theta} \qquad (28)$$

where θ is the electrical distance between the minima with the line short-circuited and with the load connected. It is positive when the load minimum is on the generator side of the short-circuit minimum.

When VSWR is greater than 10 tan θ, the following approximation is valid:

$$R_x \cong \frac{Z_0}{(VSWR)_e \cos^2\theta} \qquad (29)$$

$$X_x \cong -Z_0 \tan\theta \qquad (30)$$

The equations are much more accurate than the Smith Chart, particularly when the VSWR is high.

As an example, suppose the open-circuit standing-wave ratio is 30 db, or 31.6 to 1. The VSWR with the unknown connected is 25 db or 17.77 to 1, and the minimum with the unknown connected is located 0.17 wavelength on the generator side of the short-circuit minimum. Then,

$$R_x \cong \frac{50}{40.5\cos^2(360° \times 0.17)} = 5.32 \text{ ohms}$$

$$X_x \cong -50 \tan 61.2° = -90.9 \text{ ohms}$$

4.6.5 OSCILLATOR FREQUENCY SHIFTS.

In some cases, when the unknown is short-circuited and the position of a voltage minimum is measured to determine the effective position of the unknown, errors can be caused by shifts in the oscillator frequency with the change in the load impedance between the short-circuited and loaded conditions. The effect can become more serious as the length of line between the load and the slotted line is increased. Oscillators which are tightly coupled to the line can have relatively large frequency shifts. The effect can be greatly reduced by the insertion of a pad, such

as a Type 874-G10,10-DB Pad, between the oscillator and the slotted line. If the resultant decrease in input cannot be tolerated, the oscillator tuning can be adjusted to compensate for the frequency shift. The oscillator frequency can be checked on a receiver or a heterodyne frequency meter. Signal generators, in general, are loosely coupled, and the frequency shift is usually small.

4.6.6 HARMONICS.

Another possible source of error in the measurement of high standing-wave ratios is the presence of harmonics in the wave traveling along the line. Harmonics can be generated by the driving oscillator or by a non-linear unknown such as a crystal rectifier. The minima for the harmonics will not necessarily appear at the same points along the line or have the same relative amplitudes as the fundamental minima. Hence, a small harmonic content in the signal may produce a harmonic signal many times that of the fundamental at a minimum point. Therefore, if the detector will respond at all to harmonics, difficulty may be encountered. Superheterodyne receivers and the mixer rectifier detector, in general, have excellent harmonic rejection; but the tuned crystal detector may not have a large amount of rejection for various harmonics because the tuning stub has higher-order resonances. When the crystal detector is used for measurements of high VSWR's, and preferably even when a receiver is used, a good low-pass filter, such as the Type 874-F500 or -F1000 Low-Pass Filter, is required between the oscillator and the line to reduce the harmonics to an insignificant value. A good superheterodyne receiver or the Type DNT Detector is recommended when the VSWR is very high.

4.6.7 FREQUENCY MODULATION.

The presence of appreciable frequency modulation on the applied signal may produce errors when the standing-wave ratio is very high. Frequency modulation is usually produced when a high-frequency oscillator is amplitude-modulated; but, in oscillators using filament-type tubes, frequency modulation can also be caused by the filaments when heated with ac power. The amount of frequency modulation for a given degree of amplitude modulation usually increases as the oscillator frequency approaches its upper limit. The Type 1209 Unit Oscillator and Type 1021-AU Signal Generator are satisfactory for modulated signal measurements on very high VSWR's at 50% modulation, up to about 750 Mc. At the higher frequencies, reasonably large errors are produced in measurements of standing-wave ratios of the order of 500 or 1000. At standing-wave ratios below 50, the error is usually negligible if the over-all line length is short. Square-wave modulation should be used to minimize frequency modulation. The Type 1264-A Modulating Power Supply is recommended for use with the oscillators listed in Table I.

4.7 MEASUREMENT OF 50-OHM COAXIAL LINE CIRCUITS.

4.7.1 USE OF CONNECTING CABLE.

In coaxial-line measurements, the VSWR on the line, the impedance seen looking into an unknown line, or the impedance at the far end of a line may be needed. In measurements on antennas, we may want either the VSWR on a line terminated in the antenna or the actual antenna impedance. However, in most cases it is not possible to connect the antenna directly to the slotted line and an intermediate length of cable or air line must be used. The line or cable should have a 50-ohm characteristic impedance. Lengths of Type 874-A2 Cable can be used for this purpose. The connecting cable has no effect on the VSWR if it is a lossless, uniform line, hence the VSWR produced by the load is the same as that measured on the slotted line. In practice, however, the connecting cable and connectors will not be absolutely uniform but will have small discontinuities which will have some effect on the VSWR. The uniformity of lengths of Type 874-L Air Line is much better than that of coaxial cable and should be used if possible, to obtain the most accurate results. There is, also, always some loss in the connecting cable. If it is significant, a correction can be made for it, as outlined in Paragraph 4.6.2.

4.7.2 MEASUREMENT OF VSWR ON A 50-OHM LINE.

To determine the VSWR on a 50-ohm line terminated in the unknown, the following procedure can be used:

(1) Set up the equipment and tune the detector, as outlined in Paragraphs 4.1, 4.2, and 4.3.

(2) Connect the unknown directly to the slotted line, if possible, or use lengths of 50-ohm air line or cable provided with constant-impedance connectors, such as Type 874. If the unknown is fitted with other than Type 874 Connectors, use one of the adaptors listed in Paragraph 4.1.2.

(3) Check the output from the detector at a voltage minimum and maximum and determine that the generator output and probe coupling are satisfactory, as outlined in Paragraphs 3.2 and 4.3. If the indicated VSWR is greater than 10, only the voltage minimum need be measured, as the width-of-minimum method can be used.

(4) If the VSWR is less than 10, measure the relative output from the detector at several minima and maxima. Actually, only one minimum and one maximum need be measured, but because of the variations in probe coupling along the line, greater accuracy can be obtained if several minima and maxima are averaged or if the probe coupling is calibrated, as outlined in Paragraph 5.2. If the VSWR is greater than 10, use the width-of-minimum method, outlined in Paragraph 4.6.2, to determine the VSWR.

4.7.3 UNKNOWN IMPEDANCE CONNECTED AT THE END OF A 50-OHM LINE.

To obtain the actual load impedance, use the following method:

(1) Follow procedures (1) through (4) of Paragraph 4.7.2.

(2) Measure the position of the voltage minimum nearest the load end of the line.

(3) Short-circuit the end of the line at the point of connection to the unknown. Use a very low inductance metal sheet or strap, or a Type 874-WN3 or -WN Short Circuit, as described in Paragraph 4.1.3. Then find the position of a voltage minimum on the line with the line shorted and record the scale reading corresponding to the probe position (refer to Paragraph 4.5.1).

(4) Determine the difference in position, ℓ, between the minimum measured with the line shorted, or the unknown itself, and the minimum measured with the unknown connected. Divide the result by the wavelength to obtain $\frac{\ell}{\lambda}$. If several measurements are to be made at different frequencies on the same circuit, the over-all electrical line length between any point on the slotted line and the short circuit can be determined. Then the line needs to be short-circuited only once.

(5) On the 50-ohm Smith Chart, determine the radius of the circle on which the impedance must lie from the scale labeled STANDING WAVE RATIO, located at the bottom of the chart. Draw a circle having this radius on the chart, with its center at the center of the chart. (Refer to Paragraph 2.3.4.2.) The transmission-line equations presented in Paragraph 2.3.3 can be used in place of the Smith Chart. (The 50-ohm impedance version is considered here.)

(6) Note whether the minimum found with the line shorted lies on the generator side or on the load side of the minimum found with the load connected. If the short-circuit minimum lies on the load side, travel from zero around the circle along the WAVELENGTHS TOWARD LOAD scale the number of wavelengths found in Step (7). If the minimum lies on the generator side, travel in the opposite direction along the WAVELENGTHS TOWARD GENERATOR scale. Draw a line from this point to the center of the chart, as in Figure 7.

(7) Find the impedance in ohms of the unknown from the coordinates of the intersection of the line drawn in Step (9) and the circle drawn in Step (8). If the admittance is desired, travel around the chart another 0.25 wavelength and draw another line to the center of the chart, or use the admittance chart as outlined in Paragraph 2.3.4.4 (Figure 8). The coordinates of the intersection of this line with the circle multiplied by 0.4 are the components of the admittance of the unknown in millimhos.

4.7.3.1 Example of Antenna Impedance Measurement, Low VSWR. The antenna is a stub mounted perpendicular to a ground plane. At the ground plane the stub is connected to the center conductor of a short section of 50-ohm coaxial line which terminates in a Type 874, 50-Ohm Connector. Since it is not practical to bring the slotted line close enough to the antenna to make a direct connection between the slotted line and the instrument, a 3-foot length of 50-ohm coaxial cable is used to make the connection. (For the best accuracy, the cable should be as short as possible and, if possible, sections of Type 874-L30 Air Line should be used in place of the cable.) The generator is a Type 1209 Unit Oscillator modulated by a Type 1264-A Modulating Power Supply. The detector is a commercially available VSWR indicator used with the built-in crystal detector. The Type 1232-A Tuned Amplifier and Null Detector is also a suitable detector when the VSWR of the unknown is less than 1.8 (5 db). A Type 874-D20 Adjustable Stub is used to tune the crystal. The oscillator is set to operate at 750 Mc and the stub is adjusted for maximum output with the cable disconnected from the slotted line. The probe penetration was previously set at 30% (6 turns out from the center conductor), at which position it has no appreciable effect on the measurements. The antenna is then connected and the checks made for square-law operation.

For an accurate measurement of the VSWR, the probe is set to the voltage maximum nearest the load, and the gain is adjusted to produce a meter reading of 1 db. The probe position at this point is found to be 35.22 cm. The probe is then moved in one direction until a voltage maximum is found and the meter reading is recorded.

The probe is then moved to each of the voltage maxima and minima found on the line and the meter readings obtained are 1.0, 6.3, 0.8, 6.1, 1.2, and 6.5. The VSWR is half the average difference in the attenuator settings or

$$1/2\left[\frac{6.3+6.1+6.5}{3}-\frac{1.0+0.8+1.2}{3}\right]=2.65\,\text{db}$$

$$=1.36$$

(For greater accuracy, the variation in probe coupling can be calibrated, and corrections made, as outlined in Paragraph 5.2.)

The effective position of the measured minimum with respect to the load is then measured by short-circuiting the line at the antenna by means of a copper disk with a slot in it. The approximate position of the minimum is found. The gain is then increased to improve the resolving power. (The minimum position can be determined accurately by measuring the position of the two equal-output points, one on either side of the minimum. In this case, the minimum occurs at 36.12 cm.

In order to calculate the antenna impedance, the wavelength must be accurately known. It can be determined from the frequency by the equation:

$$\lambda = \frac{3 \times 10^4}{f_{Mc}} \quad \text{in cm}$$

where f_{Mc} is the frequency in megacycles. It can also be measured on the line by obtaining the distance between minima, as outlined in Paragraph 4.4. In the example under consideration, the wavelength is 40.00 cm.

The pertinent information, therefore, is:

VSWR = 2.65 db.
Position of minima with load connected = 35.22 cm.
Position of minima with short-circuit at load = 36.12 cm.
λ = 40.00 cm.

The impedance of the antenna is calculated as outlined in Paragraph 2.3.4.2. The radius on the Smith Chart, corresponding to 2.65 db, is found from the scales below the chart and the circle drawn on the chart, as shown in Figure 17. The position of the minimum with respect to the short-circuit minimum is $\frac{36.12 - 35.22}{40} = 0.00225$ wavelength toward the load. The antenna impedance is, therefore, 36.8 - j3.5 ohms.

In this case, the loss in the line between the antenna and the slotted line is negligible. In cases in which it is not, a correction can be made as outlined in Paragraph 4.6.3.

4.7.3.2 Measurement of the Impedance of an Antenna Having High VSWR. The same antenna measured in the previous example, when measured at 350 Mc, shows a high VSWR. The preliminary adjustments are the same as indicated in the previous example, but when the VSWR is found to be greater than 10, the width-of-minimum method is used. The probe is set to a voltage minimum near the load and the generator voltage is increased to a maximum.

To make the measurement, the probe is set at the voltage minimum and the gain is increased until the meter reads about half scale. The probe is then moved to the right of the minimum, beyond the point at which the meter reads full scale. If the Type 874-LV Micrometer Vernier is available, it should be adjusted so the plunger contacts the unpainted surface on the edge of the carriage. The carriage is then moved continuously to the left, using the micrometer vernier (or the knob, if a micrometer vernier is not used) and the meter reading at the minimum is noted. The gain is set to make the minimum read exactly 6 db on the meter. The carriage is then moved to the right until the meter reads off scale, then moved to the left by means of the micrometer vernier or the knob. The scale or vernier readings corresponding to the 0-db meter readings on each side of the null are recorded. The meter indication at the minimum should be 6 db. If it is not, the gain is readjusted to make it 6 db, and the measurement is repeated.

In the measurement in question, the minimum occurs at a scale reading of 42.40 cm and the micrometer vernier readings for the two 0-db meter readings are 2.111 and 0.632 cm. The distance between the twice-power points, Δ, is then 1.479 cm. The wavelength, λ, at 350 Mc is 85.7 cm. The VSWR, from Equation (22), is then

$$\text{VSWR} = \frac{\lambda}{\pi\Delta} = \frac{85.7}{\pi \times 1.479} = 18.46$$

When the antenna is shorted, a minimum is found at 13.09 cm. The antenna impedance is then calculated using the Smith Chart or the transmission-line equations, as outlined in Paragraphs 2.3.3 and 2.3.4.2. On the Smith Chart, the radius of the circle corresponding to a VSWR of 18.46 is drawn on the chart, as in Figure 17. The minimum with the antenna shorted is $\frac{42.20 - 13.09}{85.7} = 0.340$ wavelength toward the generator from the minimum found with the antenna unshorted. Traveling around the circle on the Smith Chart a distance of 0.340 wavelength toward the generator, the unknown impedance is found to be 9.0 - j78 ohms.

More accurate results can be obtained by use of Equations (15a) and (15b), Paragraph 2.3.3. Here $\Theta = -360° \times 0.340 = 122.4°$, and $\tan \Theta = 1.576$. Since $\frac{\tan \Theta}{\text{VSWR}}$ is less than 0.1 and the VSWR is greater than

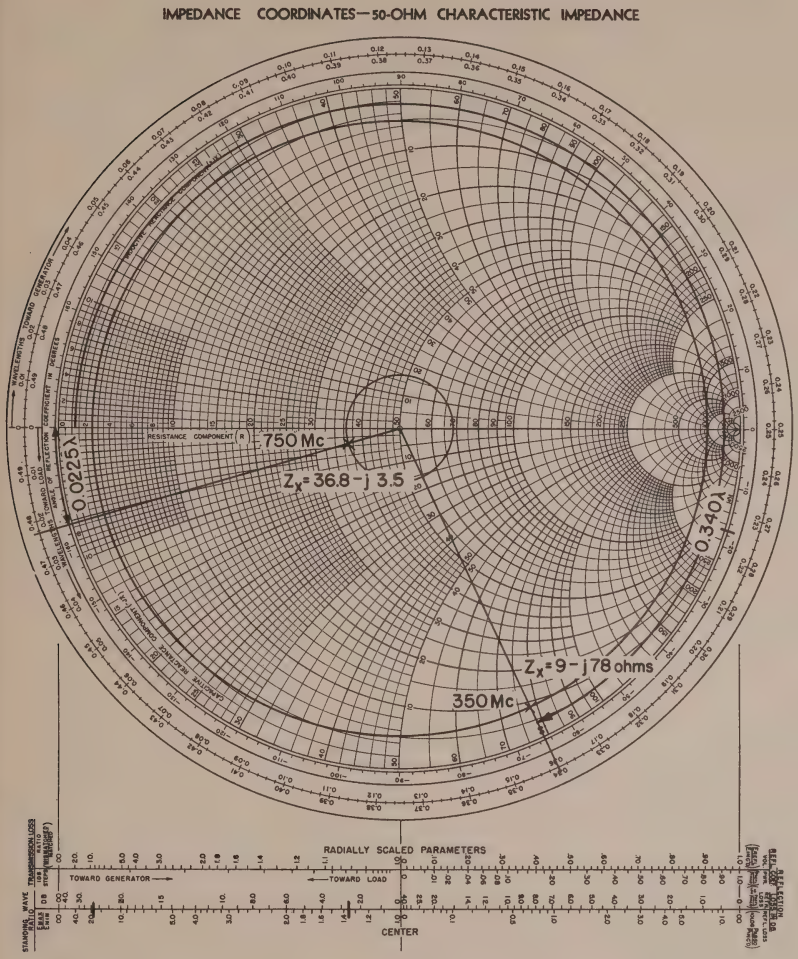


Figure 17. Example of the use of the Smith Chart to calculate antenna impedances. (See Paragraphs 4.7.3.1 and 4.7.3.2.)

10, the approximate form can be used. Also, Θ is negative, since it lies on the load side of the short-circuit minimum.

Therefore,

$$R_x = \frac{Z_o}{VSWR \cos^2\theta} = \frac{50}{18.46 \cos^2(-122.4°)}$$

$$= 9.4 \text{ ohms}$$

$$X_x = -Z_o \tan(-122.4°) = -78.8 \text{ ohms}$$

If the cable is long enough to have appreciable loss, corrections can be made as outlined in Paragraph 4.6.3.

4.7.4 MEASUREMENT OF THE INPUT IMPEDANCE TO COAXIAL-LINE CIRCUITS.

To measure the input impedance to a coaxial-line circuit, connect the circuit directly to the slotted line by means of a coaxial connector. Then use the procedure outlined in Paragraph 4.7.3. In this measurement, the point in the connector at which the impedance is to be obtained must be specified, because the impedance may vary appreciably from one point to another in the connector. In many cases, it is ad-

vantageous to measure the impedance at the front face of the polystyrene bead in the unknown connector. (Refer to Paragraph 4.1.3.) In order to determine the impedance at this point, the electrical distance from the insulator in the connector and the position of a voltage minimum on the slotted line must be found.

To determine the electrical distance, measure the physical distance between the two points in question and add 0.48 cm to the length obtained to account for the lower velocity of propagation in the insulators at the end of the slotted line.

Another more accurate method of determining the effective electrical distance is to short-circuit the end of the slotted line with a Type 874-WN Short Circuit and then determine the position of a voltage minimum on the slotted line, as outlined in Paragraph 2.3.3. The short circuit is made at the face of the bead in this unit.

Measure the VSWR and calculate the unknown impedance, as outlined in Paragraph 4.7.3.

4.8 MEASUREMENTS ON COMPONENTS AND LUMPED CIRCUITS.

4.8.1 PROCEDURES.

The Type 874-LBA Slotted Line can be used to measure the impedance of components of all types. At high frequencies, this type of measurement is complicated by many factors, the most important of which generally are: (1) the position of the element with respect to ground, leads, and other circuit elements can have a large effect on the impedance of an element, and (2) the reactances of leads used to connect the component to the measuring device, any leads which may be part of the component under test, and the stray capacitance of the measuring terminals and supplementary leads may also appreciably affect the measurements.

To minimize the effects of the first difficulty, the component should be measured while mounted in the position in the circuit in which it is to be used, or under as similar conditions as possible. One method of measuring a component in position in a circuit is to connect it to the slotted line by means of a length of flexible cable or rigid coaxial line, as shown in Figure 18. The rigid line is preferred, as its characteristic impedance is more uniform. The impedance is measured, as outlined in Paragraph 2.3.4.2. The line is short-circuited at its load end by one of the methods shown in Figures 13a and 13b.

The supplementary leads used to connect the component to the end of the coaxial line should be as short as possible to minimize the effects of the lead and terminal reactances.

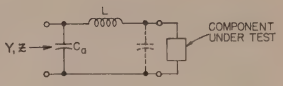
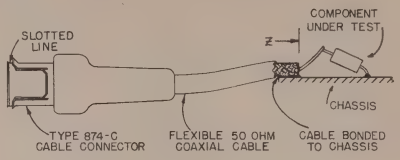


Figure 18. Approximate equivalent circuit of connecting lead reactances encountered when components are measured.



The leads referred to do not include those normally used to connect the unknown to the circuit. If the supplementary leads are short, the stray reactances can be considered as lumped into two elements: a shunt capacitance across the end of the line, and an inductance in series with the line, as shown in Figure 18. The lead and terminal reactances affect the measured impedance, Z_m, as can be seen from the equivalent circuit in the figure. In order to determine the actual impedance of the unknown, the measured impedance should be corrected for the effects of the lead and terminal reactances, using the following equations:

$$R_x = \frac{R_m}{D} \tag{31}$$

$$X_x = \frac{X_m\left(1 - \frac{X_m}{X_a}\right) - \frac{R_m^2}{X_a}}{D} - X_L \tag{32}$$

where

$$D = \left(1 - \frac{X_m}{X_a}\right)^2 + \left(\frac{R_m}{X_a}\right)^2 \tag{33}$$

$$X_a = -\frac{1}{\omega C_a} \quad \text{ohms} \tag{34}$$

$$X_L = \omega L \quad \text{ohms} \tag{35}$$

where L is the magnitude of the lead inductance in henrys and C_a is the magnitude of the shunt capacitance in farads.

If the admittance of the unknown is desired, rather than the impedance, the admittance, Y_m, appearing across the end of the line, is calculated from the VSWR and from the position of a voltage minimum, as outlined in Paragraph 2.3.4.4. The following equations should be used to correct for the lead reactances:

$$G_x = \frac{G_m}{D} \tag{36}$$

$$B_x = \frac{B'_m \left(1 - \frac{B'_m}{B_L}\right) - \frac{G^2_m}{B_L}}{D} \tag{37}$$

where

$$D = \left(1 - \frac{B'_m}{B_L}\right)^2 + \left(\frac{G_m}{B_L}\right)^2 \tag{38}$$

$$B'_m = B_m - B_a \tag{39}$$

$$= B_m - \omega C_a \times 10^3 \quad \text{millimhos}$$

$$B_L = -\frac{10^3}{\omega L} \quad \text{millimhos} \tag{40}$$

where C_a and L are as defined in the previous paragraph. All admittance components are in millimhos.

The magnitudes of the lead and terminal reactances or susceptances can be determined from measurements of the reactance seen with the leads short-circuited by a low-inductance copper sheet at the point of connection to the unknown, and the reactance seen with the leads open-circuited at the point of connection to the unknown. The inductive reactance is measured when the leads are short-circuited and the capacitive reactance is measured when the leads are open-circuited. For this approximation to hold, the lead-capacitive reactance should be greater than five times the lead-inductive reactance.

A somewhat better approximation can be made if the lead capacitance is assumed to be distributed between the two ends of the leads, as shown by the dotted capacitor of Figure 19. The ratio of the two capacitances can be estimated from the physical configuration of the circuit.

An even better approximation can be made when the leads are reasonably long, if the inductance and capacitance are assumed to be uniformly distributed and the leads are treated as a section of transmission line. The characteristic impedance, Z_o, of this line and the tangent of the electrical length, tan Θ, are related to the short- and open-circuit impedances, Z_{oc} and Z_{sc}, by the expressions:

$$Z_o = \sqrt{Z_{oc} Z_{sc}} \tag{41}$$

$$\tan\theta = \sqrt{\frac{Z_{sc}}{Z_{oc}}} = \frac{X_{sc}}{Z_o} \tag{42}$$

Equation (12) or the Smith Chart can be used to correct the measured impedance for the effect of the equivalent section of transmission line. If a Smith Chart designed for lines having a 50-ohm impedance is used, the measured values should be divided by $\frac{Z_o}{50}$ before entering the chart and the resultant corrected impedance multiplied by $\frac{Z_o}{50}$. In most cases the capacitance is not uniformly distributed but the approximation usually gives reasonably accurate results. A normalized Smith Chart is better suited to this application.

In most cases more accurate measurements can be made by use of the Type 874-M Component Mount, shown in Figure 19, on which the component or lumped circuit can be mounted. The end of the center conductor of a section of air line is used as

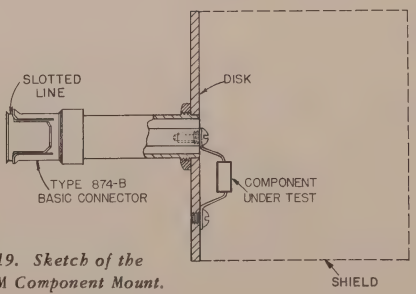


Figure 19. Sketch of the Type 874-M Component Mount.

the ungrounded terminal, and the outer conductor is extended in the form of a disk for a ground plane. The line can be short-circuited at the terminal by means of a very low inductance disk (supplied) or the mount can be disconnected and replaced by a Type 874-WN3 Short-Circuit Termination Unit. The distance from the front face of the polystyrene bead in the connector mount is located 3 cm away from the ground-plane surface; hence, the termination unit referred to places a short-circuit effectively at the ground-plane surface when it is substituted for the component mount.

A correction must be made for the reactance of supplementary leads, as previously outlined.

To remove the coaxial-line section from the ground plate, loosen the locking nut. It can then be installed in any other plate if a 3/4-27 tapped hole is provided.

4.8.2 EXAMPLE OF MEASUREMENT OF A 200-OHM RESISTOR AT 600 MC.

In this case, the resistor is mounted on a Type 874-M Component Mount, shown in Figure 19, which is connected to the slotted line. The built-in crystal detector is used with a VSWR indicator. A block diagram of the setup is shown in Figure 10. The stub is tuned with the slotted line open-circuited, as indicated in Paragraph 4.2. The unknown is connected and the input power is adjusted to keep the maximum excursion of the crystal within the square-law range. Averages of several VSWR readings are taken to minimize the effect of the variation in probe coupling along the line, and an average reading of 3.16 is obtained.

The component mount is then disconnected, the Type 874-WN3 Short Circuit is connected to the slotted line, and the position of a voltage minimum is located. The position of the minimum nearest the load is found to be at 51.20 cm. Therefore,

$$\text{VSWR} = 3.16$$

$$\frac{\ell}{\lambda} = \frac{51.20 - 40.25}{50} = 0.219 \text{ wavelength}$$

The measured resistance and reactance, calculated by the use of the Smith Chart, are:

R_m = 118 ohms; X_m = -66 ohms.

In this case, the impedance directly across the ends of the resistor is needed. However, the resistor is connected to the mount by means of its own leads, which affect the measurements. Since it is not desirable to clip the leads at the ends of the resistor to measure the lead reactances, the resistor is removed and identical leads are substituted. The position of the minimum on the line is determined with the leads open-circuited and is found to be 39.90 cm. The ends of the leads are short-circuited by spot-soldering a copper sheet about three inches in diameter to the ends of the leads and the minimum position is found again. In this case it is at 32.95 cm.

The short-circuit reactance, X_{sc}, calculated from the Smith Chart, is +57 ohms. The open-circuit reactance, X_{oc}, is -330 ohms. The actual impedance appearing across the resistor terminals is then calculated by the use of Equations (31) and (32).

$$R_m = 118 \text{ ohms}$$

$$X_m = -66.0 \text{ ohms}$$

$$X_L = X_{sc} = +57 \text{ ohms}$$

$$X_a = X_{oc} = -330 \text{ ohms}$$

$$D = \left(1 - \frac{-66}{-330}\right)^2 + \left(\frac{118}{330}\right)^2 = 0.768$$

$$R_x = \frac{118}{0.768} = 154 \text{ ohms}$$

$$X_x = \frac{-66\left(1 - \frac{-66}{-330}\right) - \frac{118^2}{-330}}{0.768}$$

$$= \frac{-57}{0.768} = -72.2 \text{ ohms}$$

The measured resistance is less than the dc value of 200 ohms, due to the shunt capacitance of the resistor itself.

SECTION **5**

MISCELLANEOUS

5.1 OPERATION AT FREQUENCIES BELOW 300 Mc.

Since the probe travel is only 50 cm, it will not always be possible to measure both a voltage minimum and maximum on the line at frequencies below 300 Mc, as the range of travel of the probe is one-half wavelength at 300 Mc. At frequencies below 150 Mc, where the line is less than a quarter of a wavelength, it will never be possible to measure both a voltage maximum and minimum on the line directly. If both a voltage minimum and maximum do not appear on the line at frequencies above 150 Mc, additional lengths of Type 874-L30 and -L10 Air Lines can be inserted between the line and the load until both a minimum and a maximum do appear. Of course, if the VSWR is greater than 10, only the minimum need appear on the slotted section of line, because the measurement can be made by the width-of-minimum method.

At frequencies below 150 Mc, lengths of air line can be inserted between the line and the load until either a minimum or maximum can be measured. Sections of air line are then transferred to the other side of the slotted line, that is, between the line and the generator, until the maximum or minimum appears and can be measured. The sections are transferred, rather than removed, to keep the load on the oscillator and, hence, the relative voltage amplitude on the line, constant.

A somewhat better solution is to use two slotted lines and add sections of air line between them or between one of them and the load until a minimum appears on one line and a maximum on the other. The probes are set at the respective maximum and minimum and the outputs from the detector and the position of the probe at the minimum are recorded. A Type 874-WM Termination Unit is then connected to the end of the line and the outputs of the two detectors again recorded. Since the voltage is constant all along the line with the termination connected, the probe couplings in this case are proportional to the outputs if the detector is linear. If the detector is square-law, the probe couplings are proportional to the square roots of the outputs. The outputs observed with the load connected can then be corrected for any difference in coupling. This calibration corrects for differences in probe penetration, differences in probe couplings, and differences in sensitivity of the detectors.

The Type 874-D20 Stub will tune the crystal rectifier down to 275 Mc. The Type 874-D50 Stub will tune down to 125 Mc. Additional lengths of air line can be inserted in series or in shunt, using a Type 874 Tee for operation at lower frequencies. With the long stub in place, smoother operation of the carriage is obtained if the whole slotted line is tilted slightly forward to make the stub almost vertical.

5.2 CALIBRATION OF THE VARIATION IN PROBE COUPLING.

The variation in probe coupling along the line can be calibrated and the measurements very easily corrected for the variations. A 1000-cycle signal of at least 10 volts from the audio oscillator is applied to the slotted line whose load end is open-circuited. The tuning stub and crystal are removed and the input to the amplifier (Type 1232-A is suitable) is connected directly to the connector normally used for the tuning stub. The variation in indication on the amplifier meter is then recorded as a function of the probe position. The curve thus obtained can be applied to rf measurements. In this calibration, the crystal is not used and the output is directly proportional to the coupling. Therefore, the correction factor measured should be applied to rf measurements after the correction has been applied for the square-law rectification characteristic.

The variations in probe coupling will change somewhat as the probe penetration is varied. Hence, for most accurate results, the calibration curve should be made with the same probe penetration as was used in the rf measurements.

SECTION **6**

SERVICE AND MAINTENANCE

6.1 GENERAL.

The two-year warranty given with every General Radio instrument attests the quality of materials and workmanship in our products. When difficulties do occur, our service engineers will assist in any way possible.

In case of difficulties that cannot be eliminated by the use of these service instructions, please write or phone our Service Department, giving full information of the trouble and of steps taken to remedy it. Be sure to mention the serial and type numbers of the instrument.

Before returning an instrument to General Radio for service, please write to our Service Department or nearest district office (see back cover), requesting a Returned Material Tag. Use of this tag will ensure proper handling and identification. For instruments not covered by the warranty, a purchase order should be forwarded to avoid unnecessary delay.

6.2 REPLACEMENT OF CRYSTAL RECTIFIER.

The Type 1N23B Crystal Rectifier is mounted in the carriage (See Figure 9a), where it is held in place by a spring. To remove the rectifier, first unscrew the crystal cover on the back of the carriage and then pull the rectifier from its socket.

The crystal can be checked with an ordinary ohmmeter. Measure the resistance with both polarities of applied dc voltage. The resistance should be below 700 ohms in one direction and above 15,000 ohms in the other.

6.3 CLEANING AND LUBRICATION.

The Slotted Line should be kept in its storage box or covered when not in use to keep dirt from accumulating on the carriage track. The track should be cleaned and lubricated occasionally for best performance.

The felt washers shown in Figure 9a are lubricated through the oil holes provided. Use a light oil and keep the oil ports filled so that there is a light oil film on the outer tube. It may occasionally be necessary to tighten the retaining rings to keep the felt washers in contact with the tube. Do not tighten them too much, or they will make it difficult to slide the carriage, causing backlash.

When the track needs cleaning, spread a coat of kerosene or light oil, such as clock oil, over the whole outside of the center conductor. Use a pipe cleaner or a cloth. Then slide the carriage back and forth several times to dislodge any dirt caught in the felt rings. Finally, wipe the track dry with a cloth. Repeat this procedure until the cloth does not pick up any dirt.

If the line is very dirty, remove and clean the felt washers. To remove them, unscrew the retaining washers at both ends of the carriage (see Figure 9a) and pull out the felt. Clean the felt in a solvent. When replacing the felt washers, flatten them out and push them into place. Reload the felt washers with a light oil through the oil holes at the ends of the carriage.

An oil port at the bottom of the carriage permits lubrication at the point of contact with the tie bar. This is especially important if the slotted line is motor driven.

The slot in the outer conductor can be cleaned with a pipe cleaner.

If the inside of the tube needs cleaning, remove the connectors at both ends as well as the center conductor and unscrew the probe about six turns. Pass a cloth attached to a string through the tube. Do not perform this operation unless it is really necessary; it requires care and readjustment of the center conductor after the line is reassembled.

6.4 REMOVAL OF CENTER CONDUCTOR.

Before or during disassembly of the line, mark the center conductor, both teflon beads, and both end-supporting sections, so that they can be reassembled with their original orientations.

To remove the connectors, unscrew the threaded ring (coupling nut) at the base of the connector, and pull off the outer connector sections. Then carefully pull the inner connector sections and insulators out of the line. (This may be difficult because the inner teflon insulator is a press fit.) Then remove the center conductor. (See Figure 20.)

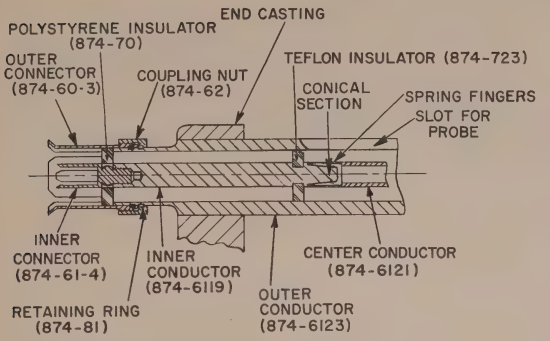


Figure 20. Sketch of end section of the line showing the supporting insulators and conical section.

If possible, replace the Type 874-70 polystyrene insulators at the base of the inner connectors with new ones before reassembling the line.

Be careful to reassemble the line with the original orientations. Insert the inner conductor part way into the right-hand end of the line, and slip the spring fingers over the conical section on the right-hand inner conductors. Then push the inner conductor (with Type 874 Connector on the end) into the tube until the polystyrene insulator is flush with the end of the tube. Align the slots in the insulator and tube, and fasten the outer connector section in place with the coupling nut.

Slide the left-hand inner conductor into the other end of the line until its end almost contacts the end of the center conductor, as seen through the large slot. Bend a piece of wire into a shallow hook, insert it through the slot, and hook it around the end of the center conductor. Lift the center conductor so that it will slip onto the conical section, and carefully push the inner conductor into place. Be sure that the conical section enters the hole in the end of the center conductor without damaging the spring fingers. Then align the slots, replace the outer connector section, and lock it in place.

If it is necessary to adjust the center conductor, rotate it until the variation in probe coupling is at a minimum. To raise or lower the ends of the center conductor, rotate the teflon beads, which are slightly eccentric. Check the variation in probe coupling at 1000 cps, as outlined in Paragraph 5.2.

To rotate the center conductor, insert a thin blade through the slots between the spring fingers (accessible through the slot in the outer conductor). A prying motion will rotate the center conductor. Be careful not to damage the spring fingers.

6.5 CENTERING OF PROBE IN SLOT.

To check the centering of the probe shield, hold the line up to a light and sight from one end along the slot. Move the carriage along the line and observe the centering of the probe shield.

If the probe is not centered, unscrew the large screws that tighten the clamps on the end casting, loosen the outer tube in its mounting, and rotate it slightly. An ell or tee inserted as a handle at one end may make it easier to rotate the line.

6.6 SPRING ADJUSTMENT.

If the coupling seems to vary as the direction of the carriage is changed, the springs bearing on the nylon plugs at the bottom of the carriage casting (see Figure 9a) may not be compressed enough. To check this, note if the output returns to its original value when the carriage is rocked sideways (in the direction of the tube) and then released. If the output does not return to the same value under all conditions, the springs are not compressed enough.

To adjust the springs, set the carriage over the hole near the right-hand end of the tie bar. Turn the slotted line over, and adjust the carriage so that the heads of the two setscrews in the base of the carriage are lined up with the hole. Adjust the screws with a 1/8 Allen wrench, turning them a half turn at a time, and check the effect of rocking the carriage. If the springs are compressed unevenly or too far, the carriage will not slide freely.

6.7 ADJUSTMENT OF NYLON CORD TENSION.

The nylon cord will stretch slightly with time, causing some backlash. A take-up reel on the back of the carriage can be used to adjust the cord tension. The inner flange of the reel has a number of holes around its outer edge; a pin, on the carriage body, enters one of the holes to provide a ratchet-type lock. To turn the reel, first pull it out about 1/16 inch to withdraw the pin from the hole in the flange. Then rotate the reel to produce the desired cord tension, and lock it by pushing it in so that the pin enters one of the holes.

6.8 REPLACEMENT OF NYLON CORD.

The nylon cord is very tough, and should last a long time unless it rubs against a sharp cutting edge. A spare cord is supplied with the slotted line, and additional cords can be obtained from General Radio Company. The cord is 0.045 inch in diameter and 74-1/2 inches long.

Install the cord as shown in Figures 9b and 9c. Knot the cord near one end, and thread the other end through the hole in the anchor post. Then pass the cord around the idler pulley and wrap it 1-1/2 times around the drive drum. Make sure that the end of the first turn is on the knob side of the beginning of the first turn (see Figure 9c) so that the turns travel in the correct direction on the drum. Then pass the cord around the anchor post and thread it through the hole in the outer flange of the take-up reel. Knot the cord near the end to keep it from slipping back through the hole. Then adjust the tension by pulling out the take-up reel, to disengage the pin. Rotate it clockwise until the action of the drive knob feels satisfactory. It may be necessary to slide the cord axially along the driving drum to center it properly and to prevent it from riding over the flange at one end.

RECOMMENDED ACCESSORIES

The following available accessories are recommended, to facilitate the making of measurements described in this book:

Type	Accessory	Quantity
874-D20	Adjustable Stub (required)	1
874-R22	Flexible Line	2
874-WM	50-Ohm Termination	1
874-WN	Short-Circuit Termination	1
874-WO	Open-Circuit Termination	1

TYPE 874 COAXIAL COMPONENTS

TYPE 874- CONNECTORS

CONNECTOR TYPE	CABLE TYPE: 874-A2	874-A3 RG-29/U RG-55/U RG-58/U RG-58A/U	RG-8/U	RG-9/U RG-116/U	RG-59/U RG-116/U
CABLE	-C	-C58	-C8	-C9	-C62
CABLE LOCKING	-CL	-CL58	-CL8	-CL9	-CL62
PANEL	-P	-P58	-P8	-P8	-P62
PANEL, FLANGED	-PB	-PB58	-PB8	-PB8	-PB62
PANEL, LOCKING	-PL	-PL58	-PL8	-PL8	-PL62
PANEL, LOCKING RECESSED	-PRL	-PRL58	-PRL8	-PRL8	-PRL62

Example: For a locking cable connector for RG-8/U, order Type 874-CL8.

TYPE 874- ADAPTORS

TO TYPE		874-	TO TYPE		874-
BNC	plug	QBJA QBJL*	TNC	plug	QTNJ QTNJL*
	jack	QBPA		jack	QTNP
C	plug	QCJA QCJL*	UHF	plug	QUJ QUJL*
	jack	QCP		jack	QUP
HN	plug	QHJA	UHF	7/8-in.	QU1A
	jack	QHPA	Air	1-5/8-in.	QU2
LC	plug	QLJA QLPA	Line	3-1/8-in.	QU3A
LT	plug	QLTJ			
	jack	QLTP			
N	plug	QNJA QNJL*			
	jack	QNP			
SC	plug	QSCJ QSCJL*			
	jack	QSCP			

*Locking Type 874 Connector,

Example: To connect Type 874 to a Type N jack, order Type 874-QNP.

OTHER COAXIAL ELEMENTS

Type 874-	
A2	50 Ω cable (low loss)
A3	50 Ω cable
D20, D50	20-, 50-cm adjustable stubs
EL	90° ell
F185	185-Mc low-pass filter
F500	500-Mc low-pass filter
F1000	1000-Mc low-pass filter
F2000	2000-Mc low-pass filter
F4000	4000-Mc low-pass filter
G3, G6 G10, G20	3-, 6-, 10-, & 20-db attenuators
GA	adjustable attenuator
JR	rotary joint
K	coupling capacitor
L10, L20, L30	10-, 20-, & 30-cm rigid air lines
LA	33-58 cm adjustable line
LK10, LK20	constant-Z adjustable lines
LR	radiating line
LT	trombone constant-Z line
M	component mount
MB	coupling probe
MR	mixer-rectifier
T	tee
UB	balun
VC	variable capacitor
VI	voltmeter indicator
VQ	voltmeter detector
VR	voltmeter rectifier
W100	100-Ω termination
W200	200-Ω termination
WM	50-Ω termination
WN, WN3	short-circuit terminations
WO, WO3	open-circuit terminations
X	insertion unit
Y	cliplock
Z	stand

The above is a partial listing. For complete details, refer to the General Radio catalog.

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